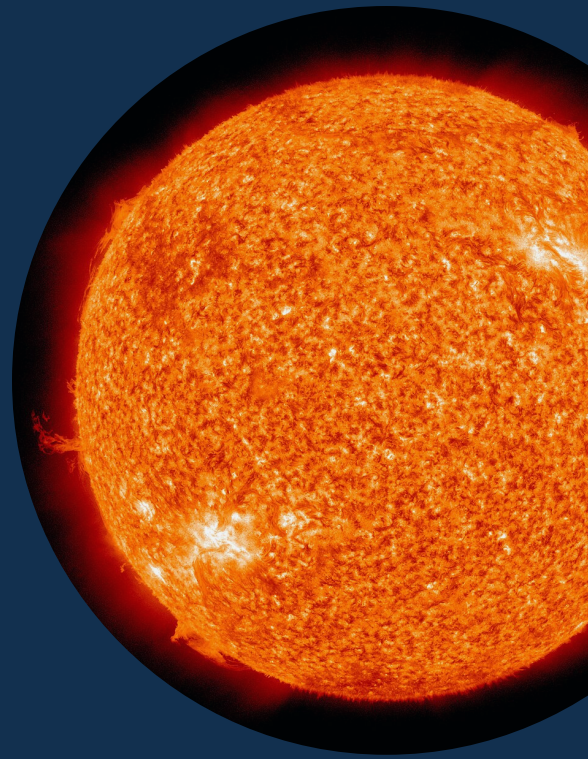

Solar Climate Forcing Cheatbook



A quick-fact guide to how the Sun's light, particles and magnetic fields shape Earth's modes, weather and storms, and what it means for the climate-change story.

Seven sections. Plain-language facts, tables and short rules.
Image: the Sun in extreme ultraviolet light, NASA/SDO.

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HOW TO USE THIS BOOK

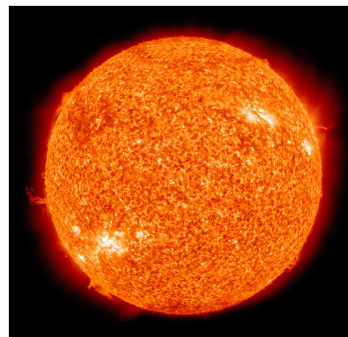
- Start with Section 7 for the one-page summary, then dip into Sections 1 to 6 for the facts behind it.
- Each section opens with a boxed rule, then short bullets and tables. Orange cells are an active Sun; blue cells are a quiet Sun.
- Image credits: NASA, NOAA and other public-domain images are marked with their source. "From the 8th book" marks charts and diagrams from the source book.

Orientation: The Sun in 60 Seconds

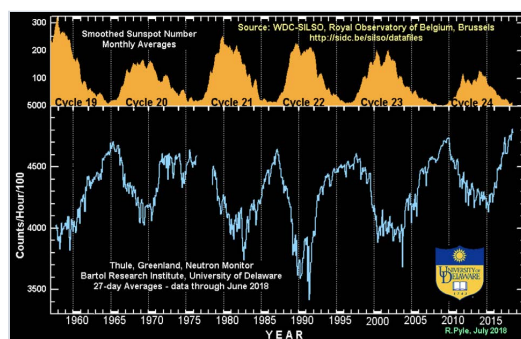
Just enough Sun to follow the rest. An **active Sun** has lots of sunspots, flares and storms. A **quiet Sun** has few. **Cosmic rays do the opposite:** more of them when the Sun is quiet.

Meet the Sun

- We feel the Sun in four ways: **gravity, light, particles** and **magnetic fields**. This cheatbook is about the last two, plus the parts of light that most people ignore (UV and X-rays).
- **Sunspots** are dark patches where the Sun's magnetic fields loop up out of the surface. They are where flares start.
- **Solar flare** = a burst of light, ranked A, B, C, M, X. Each letter is 10 times stronger than the one before. Flare light reaches Earth in about 8 minutes.
- **CME** (coronal mass ejection) = a giant cloud of Sun plasma thrown into space. It takes a few days to arrive.
- **Solar wind** = charged particles streaming away from the Sun all the time. Typical speed at Earth is 300-400 km/s. Over 600 km/s counts as fast.
- **Coronal holes** = dark gaps in the Sun's atmosphere that blast out fast solar wind.
- **Geomagnetic storm** = Earth's magnetic field getting shaken when a CME or fast stream hits it.
- **Cosmic rays** = fast particles from deep space. The Sun's magnetic field and solar wind act as a shield, so **active Sun = fewer cosmic rays; quiet Sun = more**.



The Sun seen in extreme ultraviolet light. Image: NASA/SDO



Sunspots (orange, top) and cosmic rays (blue, bottom) move in opposite directions. Image: from the 8th book (Univ. of Delaware/Bartol; SILSO)

The Sun's rhythms

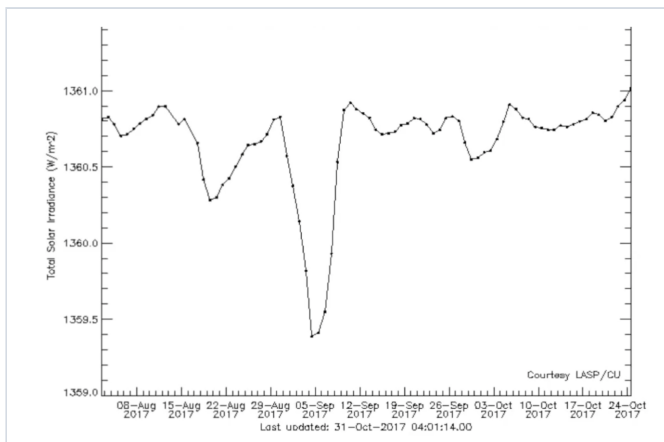
Rhythm	What it is
~27-28 days	One turn of the Sun (the equator turns faster, in about 25 days). The Sun's magnetic boundary (the current sheet) sweeps past Earth on this beat.
~6 months	Earth is more exposed to geomagnetic storms near the equinoxes than near the solstices.
~11 years	The sunspot cycle (it can run 9-13 years). Flares, CMEs and geomagnetic storms rise and fall with it. Geomagnetic activity tends to peak in the declining phase after sunspot maximum.
~22 years	The Hale cycle: the Sun's magnetic poles flip every ~11 years, so a full magnetic cycle is two sunspot cycles.
~80-88, ~200, ~400-440 years	Longer swings in solar activity (the ~80-88 year one is the Gleissberg cycle; ~400-440 years is the grand solar cycle).

- The 1900s were a **grand solar maximum**, the highest solar activity since the last ice age ended more than 10,000 years ago. The Sun is heading into another **grand minimum** this century.

The "solar constant" problem (TSI)

- **TSI** (total solar irradiance) is the total sunlight arriving at the top of the atmosphere: about **1361 W/m²**. Over the 11-year cycle it changes only about **0.1%** (~1.3 W/m²).
- Climate models mostly use TSI as "the Sun." The IPCC AR5 report gave the Sun about **+0.05 W/m²** of warming for 1750-2011, versus about **+2.3 W/m²** for greenhouse gases.
- **The problem:** TSI only counts sunlight. It misses X-rays, particles, the Sun's magnetic effects and cosmic-ray changes.
- During big flares TSI actually **dips**, even though X-rays and particles surge. Examples: the X17 and X28 flares of Oct-Nov 2003, and the September 2017 storms.

Solar swing	Size
TSI over the 11-year cycle	~0.1%
X-ray energy over the cycle	~10x
X-rays in short bursts	100-1000x
CMEs at sunspot minimum	only 1-10% as many
Geomagnetic storms at minimum	10-20x fewer
Cosmic rays over a cycle or an event	5-10% or more
Sept 2017 storms	tens of times normal energy overall; ~1000x in X-ray and particle delivery



TSI during the September 2017 storms: a deep dip, while X-rays and particles surged. Image: from the 8th book (LASP/CU)

Remember: sunlight is the Sun's *smallest* swing. The bigger swings are in X-rays, particles, magnetic fields and cosmic rays. Those are the ones the rest of this cheatbook follows.

Why you should care

- The real solar forcing is **missed** during big CMEs and geomagnetic storms. Total solar irradiance shows a **false drop** in solar forcing at exactly those times.
- That false drop, and any real solar forcing on the climate, gets **blamed on humans**, because there is no solar particle tool in the climate toolbox.

SECTION 2

The Sun Impacts the Big Modes and Oscillations

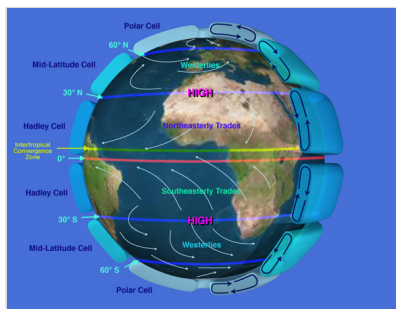
The rule: an **active Sun** nudges most big climate modes toward their **positive** phase. A **quiet Sun** nudges them **negative**. Positive phases are generally milder and steadier; negative phases bring blocking, cold outbreaks and drought. Responses can show up **1-4 years** after the solar change (some are faster, some slower), and they differ from region to region.

2a. The plumbing: Hadley and Walker cells, jets, polar vortex

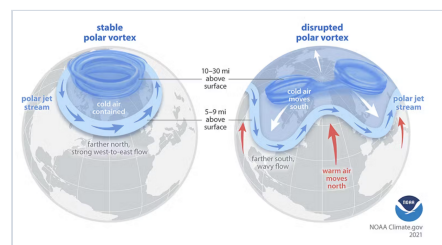
- **Hadley cells** = the big tropical overturning loops. **Walker circulation** = the east-west overturning loop over the tropical Pacific. The **jet streams** and **polar vortices** ride between the cells, near 30° and 60° latitude.
- Sun-driven changes show up as changes in **surface pressure**, jets and storm tracks. The Walker response is strongest in the **declining phase** of the sunspot cycle, when geomagnetic activity peaks.

	Active Sun	Quiet Sun
Hadley cells	Expand toward the poles and strengthen	Contract; colder air reaches farther toward the equator
Walker circulation	Stronger	Slows down
Subtropical jets	Faster and shifted poleward; up to ~10 m/s faster than at minimum	Weaker; more blocking
Polar vortex	Strong, tight and stable; Arctic air stays up north; jets stay flatter	Disrupted more often (sudden stratospheric warmings); jets meander and "block"
Pressure centers	Stronger pressure gradients; positive surface-pressure anomalies in the Northern Hemisphere with fast solar wind	Aleutian Low weaker and shifted east; North Pacific highs stronger
Resulting weather	Milder winters, stronger storm tracks at higher latitudes, more predictable weather	More blocking, floods and cold events (Europe and North America)

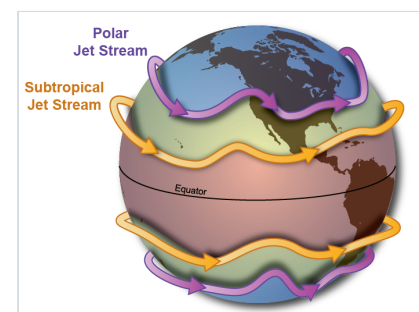
- During long solar minima, the tropical rain belt (ITCZ) shifts south and polar air moves south, cooling northern continents and confining tropical storm systems.
- Polar cell: tightens and intensifies when the Sun is active (it does not expand toward the equator).
- The jet shifts cannot be fully explained *without* the Sun.



Earth's circulation cells. Image: NASA



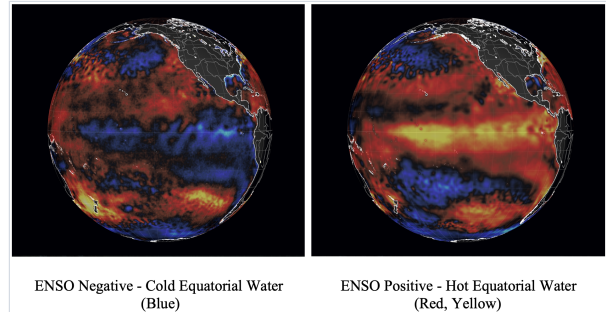
Stable (left) vs disrupted (right) polar vortex.
Image: NOAA Climate.gov



Polar jet (purple) and subtropical jet (orange).
Image: from the 8th book (NOAA/NWS)

2b. ENSO (El Niño and La Niña)

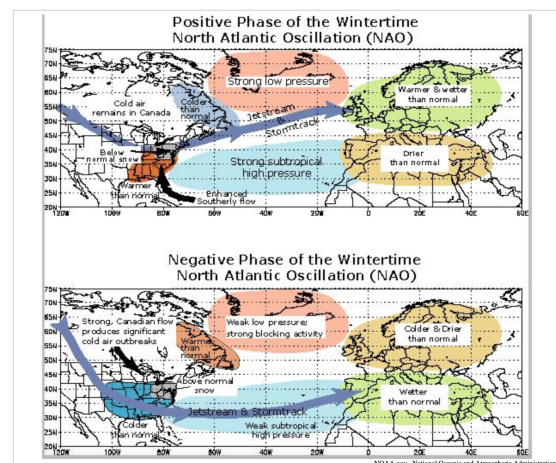
- ENSO "touches everything." It is the biggest driver of year-to-year global weather: droughts, floods, heat extremes, winter storms.
- El Niño makes the biggest spikes in global temperature. 1998 and 2015/2016 were the 2nd and 1st strongest El Niños on record.
- **Active Sun → El Niño-like** (warmer eastern Pacific). **Quiet Sun → La Niña-like**. Sunspot numbers correlate with ENSO strength and how often events happen.
- **Lag:** strong solar wind in one year goes with changes in ENSO the **next year**; the sunspot-cycle link runs ~1-4 years.
- **Solar cycle "termination"** (the handover from one cycle to the next) has been linked to the timing of La Niña and El Niño, including the recent **triple-dip La Niña** (2020-22).
- Long records show **more ENSO swings in high-activity centuries**.
- The IPCC has acknowledged the solar link to ENSO and told scientists to include it in future models.
- Nudge, not override: if a strong El Niño is due, a deep sunspot minimum mostly makes it *weaker*, not a La Niña. When solar timing and ENSO timing line up, you get the strongest events.



ENSO negative (La Niña, cold equatorial water) and positive (El Niño, warm equatorial water). Image: from the 8th book

2c. NAO (North Atlantic Oscillation)

- **Positive NAO (active Sun):** strong Icelandic Low and Azores High, strong westerlies, mild wet winters in northern Europe and the eastern US, fewer Arctic outbreaks.
- **Negative NAO (quiet Sun):** weak westerlies, blocking, colder and drier winters.
- **Lags:** NAO shifts 1-4 years after solar maximum, with a second lag of about 7 years.
- Strong flares (M and X class) and CMEs give a temporary positive NAO for about **9 days**.
- High geomagnetic activity heats the upper atmosphere, strengthens the polar vortex and reinforces positive NAO.
- The Maunder Minimum shows long stretches of negative NAO and cold in Europe and North America.
- Putting solar forcing into decadal models improves NAO forecasts.



NAO positive (top) and negative (bottom) winter patterns. Image: from the 8th book (NOAA)

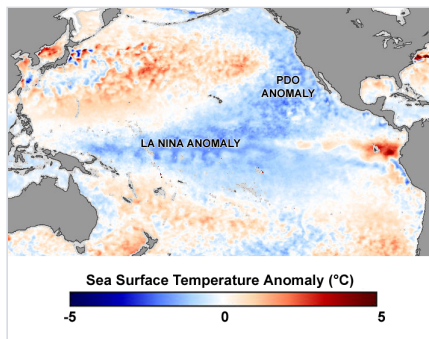
2d. Annular modes (NAM and SAM)

- NAM (Northern Annular Mode, also called the Arctic Oscillation) and SAM (Southern Annular Mode) measure how tightly the westerly winds circle each pole.
- **Active Sun:** positive NAM and SAM. Strong polar vortex and westerlies, milder mid-latitude winters, fewer cold outbreaks, stronger storm tracks in both hemispheres.
- **Quiet Sun:** negative phases. Weak vortex, cold air pushes into mid-latitudes, harsh winters.
- **SAM:** strongest solar link in **austral summer**. Positive SAM keeps cold air near Antarctica and means fewer cold events in places like Australia; negative SAM at solar minimum brings more.
- Pathways: stratospheric changes working their way down, fast solar wind and geomagnetic activity, and charged particles changing stratospheric ozone (which changes the temperature gradient and winds).

2e. PDO and AMO (the slow ocean modes)

PDO (Pacific Decadal Oscillation)

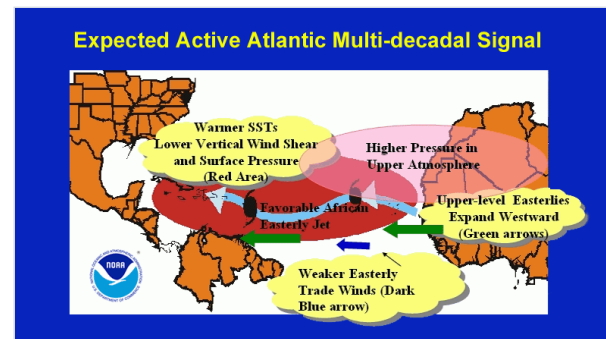
- **Active Sun:** positive PDO. Warm eastern Pacific, cool west, stronger storms on the US West Coast, milder North American winters.
- **Quiet Sun:** negative PDO. Cool eastern Pacific, La Niña reinforced, higher drought risk in the western US.
- Follows the 11-year and 5.5-year solar cycles. UV at solar max strengthens the Aleutian Low.
- PDO is one of the main routes by which solar forcing gets passed to ENSO.



Cool-phase (negative) PDO pattern with La Niña, April 2008. Image: NASA Earth Observatory

AMO (Atlantic Multidecadal Oscillation)

- **Active Sun:** positive AMO. Warmer North Atlantic, more hurricane activity, wetter Europe and North America.
- **Quiet Sun:** negative AMO. Cooler Atlantic, fewer tropical storms, more drought in North America and the Mediterranean.
- Works through the Atlantic overturning circulation (AMOC) that moves heat north.
- Shows an 11-year solar beat. The link broke down during the Little Ice Age, when solar activity was ultra-low.
- Example: Italy's groundwater recharge is higher when solar activity is higher.



The warm-AMO pattern linked to active Atlantic hurricane seasons. Image: NOAA

2f. QBO and MJO (the fast tropical rhythms)

- **QBO (Quasi-Biennial Oscillation):** a stratospheric wind over the tropics that flips between east and west every couple of years.
 - You often cannot see a solar signal in the stratosphere until you sort the data by QBO phase (east vs west). Then the pattern appears.
 - The Sun also changes the QBO: solar maximum tends to weaken the QBO's effects; solar minimum strengthens them.
 - The QBO strengthens or tempers solar effects by region, which helps explain strong and weak solar signals elsewhere.
- **MJO (Madden-Julian Oscillation):** a pulse of tropical clouds and rain that circles the globe eastward every 30-60 days.
 - Short ~27-day swings in solar UV are followed, **4-8 days later**, by more rain over the equatorial Indian Ocean and less over the western and central Pacific. The opposite follows a UV low.
 - The effect is clearest when the MJO is active.
- **Moon note:** weather cycles of 27-28 days can be partly the Moon's 28-day cycle, not the Sun's.

2g. Modes cheat table

Mode	What it is	Active Sun	Quiet Sun	Lag	Who feels it
Hadley / Walker	Tropical overturning loops	Expand, strengthen	Contract, slow	Fast to ~1-4 yr	Tropics, monsoon regions
Jets / polar vortex	Wind rivers and the winter polar cold pool	Flat, fast, stable	Wavy, blocked, vortex breaks	Fast to 1-4 yr	Europe, North America
ENSO	Tropical Pacific warm/cool swings	El Niño-like	La Niña-like	~1-4 yr	Whole world
NAO	Icelandic Low vs Azores High	Positive: mild, wet	Negative: cold, blocked	1-4 yr (+ ~7 yr)	Europe, eastern US
NAM / AO	Arctic westerly strength	Positive	Negative: cold intrusions	Short- and long-term	Northern mid-latitudes
SAM	Antarctic westerly strength	Positive	Negative: more cold	Delayed	Australia, southern oceans
PDO	Decades-long Pacific pattern	Positive: stormy West Coast	Negative: western US drought	Years to decades	North America, Pacific
AMO	Decades-long Atlantic warmth	Positive: warm, more hurricanes	Negative: cool, droughts	Decades	North Atlantic, Europe, N. America
QBO	Tropical stratosphere wind flip	Weaker QBO effects	Stronger QBO effects	Flips every few years	Sorts the solar signal by region
MJO	30-60 day tropical rain pulse	After a solar UV peak: more rain Indian Ocean, less west/central Pacific		4-8 days	Tropics

What to remember

- The Sun nudges the **plumbing** (cells, jets, polar vortex, pressure centers). The named modes (ENSO, NAO, NAM, SAM, PDO, AMO) then shift with it.
- **Active Sun = positive phases, steady weather. Quiet Sun = negative phases, blocking and cold or flood extremes.**
- Delays range from days (MJO) to 1-4 years (ENSO, NAO) to decades (PDO, AMO).
- Solar timing **nudges** natural cycles; it does not override them. Where the two line up, results are strongest.

Plain rules: active Sun = steadier weather, positive modes. Quiet Sun = blocking, negative modes, more cold and flood events. The bigger the match between solar and natural timing, the more extreme the result.

SECTION 3

The Sun Impacts Temperature, Rain, Wind and Pressure

The rule: active Sun = warmer, steadier circulation. **Quiet Sun** = cooler, more blocking, more regional extremes. There is **no single global rule** for rain: some places get hotter, others cooler, some wetter, others drier, because the Sun works through the modes in Section 2.

3a. Temperature

Global

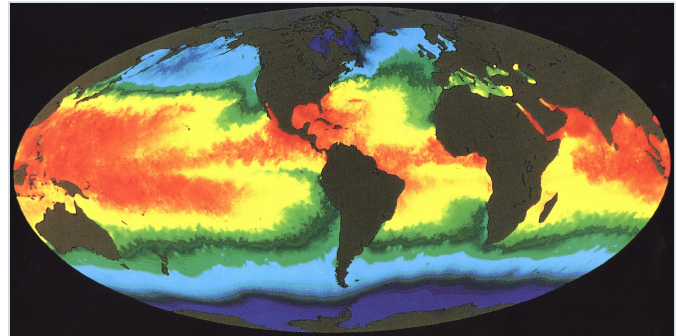
- **Active Sun warms; long solar minima cool** (the Maunder Minimum was a long cooling spell).
- The 11-year and 22-year solar cycles line up with decade-scale temperature swings. A 20-22 year swing in temperature and humidity near the tropopause is tied to the Sun's magnetic field steering cosmic rays and ozone.
- **Fast spikes:** surface temperatures have jumped during CME impacts, solar-magnetic-field changes and fast solar wind streams. Those are particle and magnetic changes, **not** sunlight changes.
- The ~1940-2000 grand maximum produced about **twice as many CMEs** as a century earlier. The 2012-2015 maximum fell back to early-1900s CME numbers.
- The **Northern Hemisphere** runs warmer at solar max, even after accounting for NAM, ENSO and the QBO. It shows up best in the **declining phase**, so geomagnetic activity (which peaks 1-3 years after sunspot maximum) is the best timing guide.

Region by region

Region	Active Sun (solar max)	Quiet Sun (solar min)
Europe, eastern North America	Milder winters (positive NAM/NAO)	"Severe winter" intensification; harsher, snowier winters
Eurasia	Warmer summers that track solar irradiance; stronger monsoons, more regional heatwaves and drought	Stronger blocking lets Arctic air in: colder winters in Russia, China, Central Asia
Polar regions (winter)	Winter polar surface temperature follows the solar cycle directly, linked to the polar vortex and solar-wind coupling	
Pacific Northwest, Canadian Prairies, Midwest US	More high-pressure anomalies: drier and warmer	Colder winters, more storms
Mexico, southwest US	Heatwave frequency and rainfall patterns swing with solar-driven circulation shifts	
Australia, South America, Antarctica	Positive SAM: warmer Australia, more Antarctic ice melt	Colder, stormier
Tropics, South Asia, Africa	El Niño-like: higher Pacific surface temperatures	La Niña: regional cooling; ENSO swings the monsoons and heatwaves

Oceans

- Solar max reinforces ocean **heat storage**; solar min lets the ocean lose heat. Sea-surface temperature follows the 11-year cycle.
- **Why the lags:** sunlight reaches down about 600 feet, and the heat can stay in the water for up to **decades**.
- **Atlantic overturning (AMOC):** strong at solar max (more warm water north, warmer Europe and North America); weaker at solar min (cooler, more storms).
- **Southern Ocean:** at max, more melt and warming; at min, more cold-water upwelling and cooling.
- Sun-driven wind and wave changes shift the upwelling zones where cold deep water reaches the surface.
- The same links show up in the Caspian Sea and the Indian Ocean (monsoon heating).



Global sea-surface temperature map. Image: NASA

3b. Precipitation

The global picture

- **Active Sun = fewer cosmic rays = fewer cloud seeds = less global cloud cover.** Quiet Sun = more cosmic rays and more cloud seeds.
- Active-Sun periods line up with stronger ENSO episodes, which reshuffles rainfall worldwide.
- Higher geomagnetic activity changes the global electric circuit, which affects cloud electrification and rain (see Section 5).
- Adding sunspot numbers to US monthly-rainfall forecast models measurably improved them.

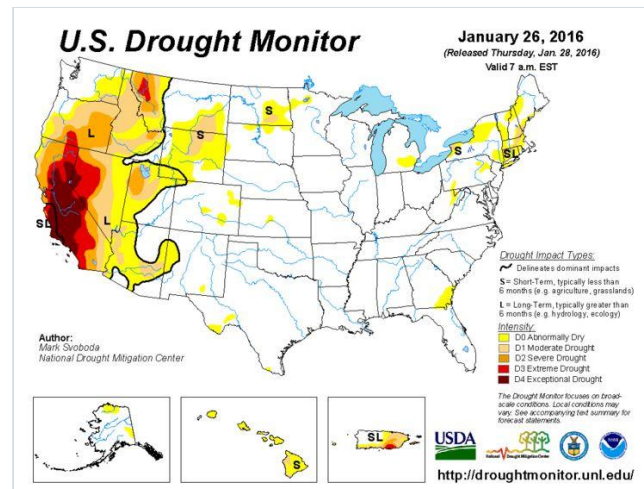
Regional rainfall

Region	Link
United States	Strong solar-cycle rainfall pattern in the northwest and southwest. Long droughts in the central and southwestern US line up with low solar activity; solar minima force droughts in the central-eastern US.
Brazil, Argentina	Brazil: high solar activity goes with less rain, on 11- and 22-24-year beats. Southern Argentina rain follows sunspots and geomagnetic activity.
Caribbean, Central America	Low solar activity = long droughts (Jamaica during the Little Ice Age, with a southward push of the Hadley cells).
Europe	Alps and western Mediterranean: more and bigger floods at solar minimum. Tuscany: higher flood risk at both solar max and min. High solar activity = warmer and drier for most of Europe, but cooler and wetter along the south coast into North Africa. High cosmic rays (quiet Sun) = cooler and wetter across most of Europe, with a 3-4 year lag. Serbia's rain tracks coronal-hole solar wind streams.
China, East Asia	Monsoon follows the 11-year cycle: solar max pushes the monsoon north and makes it more variable; stronger summer monsoon at high solar activity. Yellow River floods match geomagnetic maximum. In the Yangtze belt, extreme rain events are <i>less</i> common when sunspots are high.
India, Nepal	The tropical easterly jet speeds up at solar max and slows at min; monsoon rain follows with a delay of about 13 years in one study. Monsoon failures coincide with grand solar minima. Kerala: rain tracks sunspot number best (strongest in Solar Cycle 21, 1976-86, and in winter more than in the monsoon). Nepal: strong match to the solar cycle (correlations 0.77 and 0.76, lags of 18 and 14 months).

Middle East, Africa, Mediterranean	Iraq rain follows solar wind speed and geomagnetic indices. Nigeria rainfall and temperature show 11-, 22- and 44-year beats (dry-season rain moves opposite to solar activity). Extreme rain in Greece and Libya (Sept 2023) was tied to cosmic-ray flux and sea-surface temperature anomalies.
Crimea	Dry spells come with more cosmic rays and less solar activity; wet spells with the reverse.
Australia, Indonesia	Grand solar minima bring more extreme rain across the region.
Antarctica, Greenland	Antarctic precipitation follows solar activity, cosmic rays, ENSO and PDO. Jet-stream blocking at solar minima adds snowfall over Greenland.

Floods, drought, heat, cold: quick list

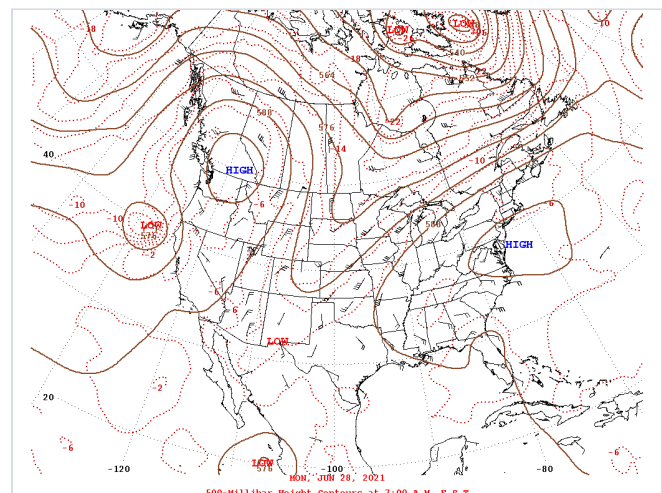
- **Floods:** Alps and Mediterranean (solar min); Yellow River (geomagnetic max); Tuscany (both extremes).
- **Drought:** central and southwest US, Caribbean (low solar); western US with negative PDO; North America and Mediterranean with negative AMO.
- **Heat:** solar-max stratospheric warming strengthens monsoons and raises regional heatwave and drought frequency.
- **Cold:** weak polar vortex, blocking, negative NAO/ NAM/SAM at solar min.
- A **grand solar minimum** can break normal monsoon patterns, bringing droughts and floods like those of the Little Ice Age.
- Indian monsoon results differ by region, because the NAO and planetary waves shift by area.



US drought map (Jan 2016). Image: US Drought Monitor / NOAA

3c. Wind and pressure

- **CME impacts** change surface pressure. Fast solar wind raises Northern Hemisphere surface pressure.
- Solar flares act more at **low latitudes**; cosmic rays, CMEs and geomagnetic activity act more at **high latitudes**, especially on pressure centers like the Icelandic Low.
- Arctic and Antarctic surface pressure follows solar irradiance, the Sun's magnetic field and solar wind streams. The effect is strongest in years of high geomagnetic activity.
- The **Siberian High** gets stronger with sunspot and geomagnetic activity.
- The interplanetary electric field links directly to polar pressure and wind changes.
- **Wind:** fast solar wind goes with more turbulent energy near the ground and bigger wind speeds and wave heights.
- The jet stream wobbles more on days of high geomagnetic activity.



A high-pressure "heat dome" over the Pacific Northwest, June 2021. Image: NOAA

Speed of response What happens

Minutes to hours	Temperature, clouds, pressure, wind, lightning and jet changes after X-rays, particles or a CME hit
1-20 years	The big modes (ENSO, NAO, PDO, AMO)
Up to decades	Ocean heat stored near the surface

Remember: temperature and rain effects mostly come *through* the modes. Wind, pressure, clouds and lightning respond faster, through particles and electricity (Sections 4 and 5).

SECTION 4

The Sun Impacts Storms: Lightning, Hail, Tornadoes, Hurricanes, Winter Storms

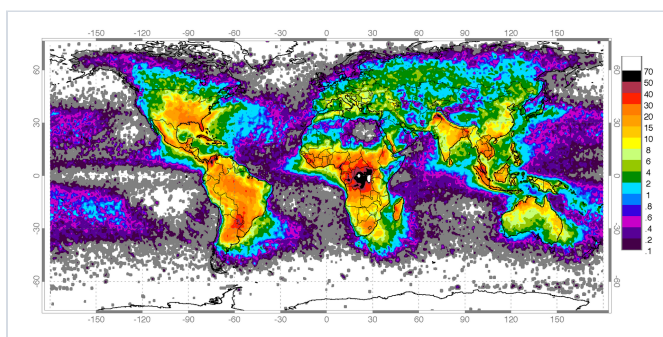
The rule: cosmic rays and particle bursts change the electricity inside clouds. Sudden jumps in solar activity (especially after quiet spells) are tied to storms getting stronger.

4a. Lightning

- Lightning follows the Sun's **magnetic polarity**, the **27-day** solar rotation (a long Japanese record shows it) and the solar cycle. Thunderstorms increase when Earth crosses the Sun's current sheet.
- **Quiet Sun = more cosmic rays = more lightning.** Lightning is directly tied to cosmic rays and moves opposite to the sunspot cycle (clearly seen across Brazil).
- **Forbush decreases** (cosmic-ray drops when a CME hits) go with **fewer** strikes in the US, Africa and worldwide. Solar particle events and ground-level enhancements cause short-term changes in lightning rates.
- Size: Europe up to **+33%** for about 40 days under fast solar wind; **+40-60%** when Earth crosses the current sheet.
- US: summer heat-driven lightning drowns out the signal. In winter the cosmic-ray link can account for about **1.6%** of strikes.
- **How:** more ionization makes air conduct better and helps ice-phase charge separation inside clouds. Lightning in turn feeds the global electric circuit.
- Both high and low extremes of solar activity can modulate lightning.



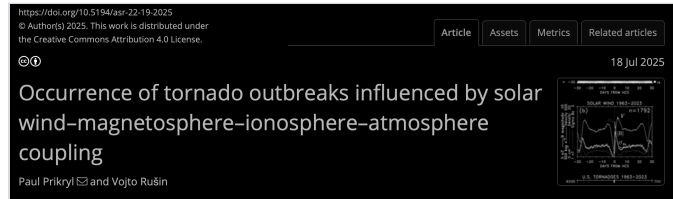
Cloud-to-ground lightning. Image: NOAA



Where lightning strikes most: global flash-rate map. Image: NASA

4b. Hail, tornadoes and severe thunderstorms

- **Hail:** lightning rate inside hailstorms depends on the storm's ice structure, and cosmic-ray ionization changes that. Lightning counts also track ice precipitation, so hail is open to the same space-weather effects as clouds and lightning.
- **Tornadoes:** a July 2025 study found tornado outbreaks influenced by solar wind-magnetosphere-ionosphere-atmosphere coupling. How: auroral excitement of the atmosphere amplifies fronts and wind shear, adding spin inside storm cells.
- **Severe thunderstorms:** higher solar output is linked to more instability and convection.
- Storms that take an electron injection from a CME squeeze can see a short local burst of lightning, hail and even tornadic activity.



The 2025 tornado study. Image: from the 8th book



Twin tornadoes. Image: NOAA

4c. Hurricanes, typhoons and cyclones

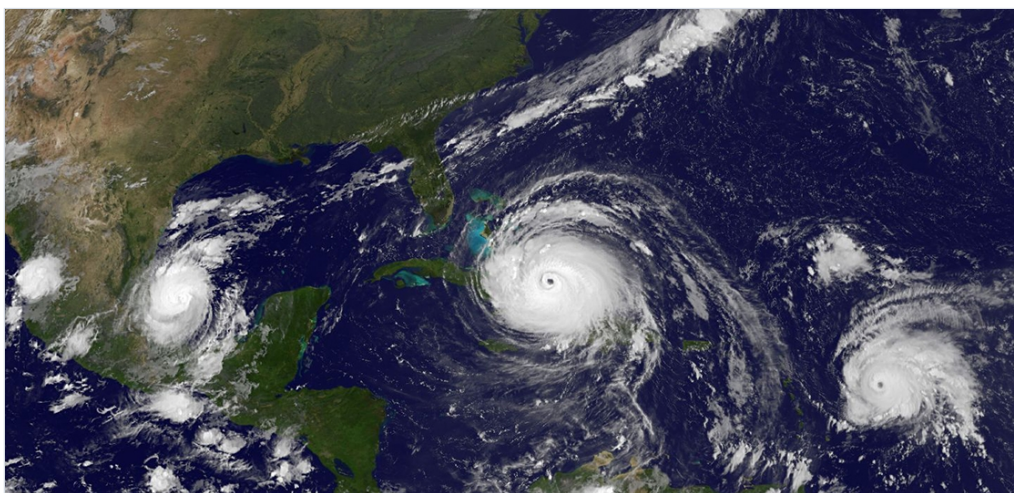
- **Links:** cloud ionization, the electric circuit, changes in the Walker circulation and jets, solar UV, and geomagnetic effects on stability, humidity and wind shear.
- **Long records:** a 300-year Taiwan typhoon record; Caribbean shipwreck records of past hurricanes; solar-cycle extremes as a predictor of Atlantic hurricane activity; Australian storm-surge records.
- **Intensity:** daily tropical cyclone intensity follows solar UV changes; high-speed solar wind streams are tied to extreme storms. One model predicts about **25%** of hurricanes from solar storm activity.
- **Student project:** in October 2017, 15-year-old Faris Wald won the \$25,000 Samueli Foundation Prize at the Broadcom MASTERS for linking coronal holes to cyclone formation.

Basin or timescale	What happens
Western North Pacific	More typhoons when the Sun is quiet : more cosmic rays, more cloud seeds, and circulation changes (Walker, subtropical jet).
North Atlantic	Active Sun and positive AMO go with more and stronger hurricanes ; negative AMO (quiet Sun) with fewer. The link varies with ocean and air conditions in each basin.
Short bursts	A sharp jump in solar activity (especially after a quiet stretch) is tied to rapid intensification and record storms.

No single rule: the link depends on basin and timescale. Tip: don't ask "how big was the solar event?" Ask "how big was the **change** from the quiet before it?"

Four case files

When	Space weather	Storm
Aug 2005	Flare and CME on Aug 22, during sunspot minimum, the day before Katrina formed	Katrina formed and intensified
Late June 2015	Rare Kp8 geomagnetic storm from several CMEs and a coronal-hole stream	Within two weeks, six cyclones at once in the Pacific
Late Oct 2015	Strong geomagnetic storm as Patricia formed	Patricia intensified to 215 mph winds, a world record
Sept 3-13, 2017	Largest flare and particle event in 12 years; days-long Kp8 geomagnetic storm	Irma formed and took an unexpected path; Maria formed Sept 16 (Jose and Katia were active too)



Hurricanes Katia, Irma and Jose on September 8, 2017, during the solar storms. Image: NOAA (GOES-16)

4d. Winter storms and blocking

- **Quiet Sun:** winter storm tracks shift toward the equator, so the Mediterranean and southern Europe get more frequent, stronger storms. Weak stratospheric heating also means a wobblier jet, blocking and cold outbreaks.
- **Active Sun:** storm tracks run farther poleward with stronger westerlies and fewer cold outbreaks.
- Geomagnetic storms and fast solar wind streams are tied to **extratropical cyclone** intensification (example: Hurricane Kate in 2015).

Remember: Lightning: quiet Sun and cosmic rays. Hail and tornadoes: ionization and aurora-driven wind shear. Hurricanes: depends on basin, and sudden solar jumps matter most.

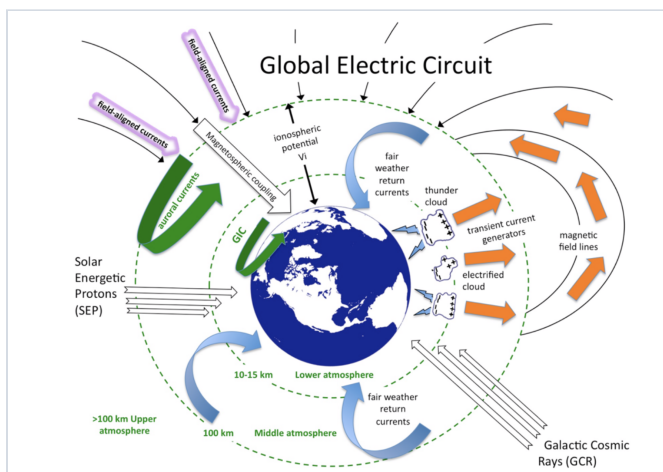
SECTION 5

The Global Electric Circuit and the Particle Forcing Model

The big picture: the Sun reaches the weather mostly through **electricity and particles**, not just warming. That explains fast effects (minutes to hours) and why models that only use sunlight miss them.

5a. The global electric circuit (GEC)

- Picture a **planet-sized circuit**. **Ceiling = ionosphere**. **Floor = the ground**. Thunderstorms keep it charged.
- Current flows **down** in high-pressure (fair-weather) areas and **up** in low-pressure cells, in columns and spirals. Lightning can push current up (sprites).
- When something hits the ionosphere (a flare, a geomagnetic storm, cosmic rays), particle counts and conductivity change, so the vertical current changes, and the weather below responds.
- **Three ways solar wind enters:** cosmic-ray modulation, high-energy electrons dropping out of the magnetosphere, and magnetosphere-ionosphere coupling at the poles.
- **Flares:** in strong flares the ionosphere's electron temperature rose 28-92% and ion temperature 18-39%. Flares also launch traveling ionospheric disturbances.
- **CMEs:** squeeze the magnetosphere and change the electric potential that drives the circuit. A CME set off a wave in the ionosphere 300 km high moving faster than 1 km/s.
- **Solar wind:** changes the downward current density.
- Ionospheric potential can swing up to **25%** over the solar cycle (via cosmic rays), and by about the same amount in **one** strong space-weather event.
- CME and electron boosts can make current channels about **8 km wide** in fair-weather high-pressure areas.
- **Antarctica is the best test case:** in winter, the solar wind's magnetic field changes polar surface pressure, temperature and downward longwave radiation at the South Pole. Geomagnetic super storms show up in the electric field at Concordia Station.
- **What changes at the bottom:** clouds, humidity, rain, pressure, temperature, wind, lightning, jet positions and storm tracks.
- **Newer findings:** sun-particle ionization over the polar caps is about **3 times higher** than first estimated, and up to **11%** of solar wind energy is transferred into Earth's geomagnetic system at the bow shock. Models leave out both.



The global electric circuit and its solar inputs. Image: from the 8th book

5b. Cosmic rays and clouds

- Cosmic-ray ionization makes aerosols that become **cloud seeds** and helps ice form. Cosmic rays change the electric fields, droplet sizes and thunderstorm strength.
- **Quiet Sun = more cosmic rays = more cloud seeds = more cloud. Active Sun = fewer.** Tropical high-altitude cloud systems track the cosmic-ray cycle.
- Early studies disagreed, but the evidence has tipped strongly toward yes since about 2014.
- **CME hit:** cosmic rays drop for days (Forbush decrease), but solar protons and electrons from the squeezed magnetosphere add ionization on the sun-facing side.
- Fast solar wind stirs up mesosphere turbulence at high latitudes; night-time cloudiness tracks geomagnetic activity, especially at low latitudes.
- CERN's CLOUD experiment tests ion-induced cloud seeding under controlled conditions.



One cosmic ray makes a shower of particles. Image: NASA (from the 8th book)

Humans accidentally tested it: since 2021 the UAE has flown drones that release electric charge into clouds. They produced significant rain in July 2021, and it made big news in 2024. It is a controlled copy of the natural cosmic-ray and electric-circuit process.



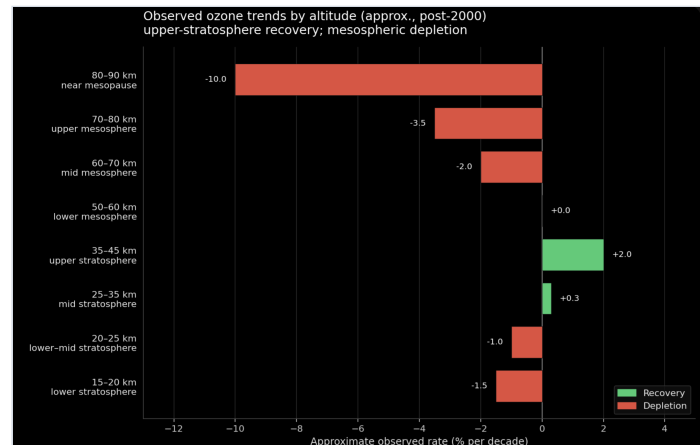
UAE rain-enhancement drone with electric-charge emitters. Image: from the 8th book

5c. Particle precipitation and ozone

- Charged particles enter at the poles (the polar cusps), ionize the air and kick off chemistry.
- Auroral energy flows toward the equator, while on the sun-facing side the squeeze pushes Van Allen belt electrons down into the atmosphere at the equator.
- **Ozone, in one paragraph:** extreme solar proton storms destroy stratospheric ozone (one study found global ozone loss after the July 2012 CME), which changes the air's electrical conductivity. Particle-driven ozone changes also alter stratospheric temperature gradients and winds, feeding the annular modes (Section 2). Cosmic rays change ozone near the tropopause, which is tied to a 20-22 year swing in temperature and humidity. The split between man-made chemicals and solar protons has been determined using altitude-dependent analysis: the lower and middle layers of the ozone layer are far less damaged than the upper ones, with the mid and upper stratosphere recovering, while the upper reaches, which are more exposed to the effects of the pole shift, take increasing damage with altitude.



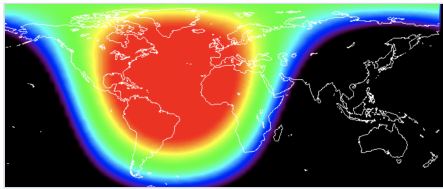
Aurora over the North Atlantic: particles entering at the poles. Image: NASA



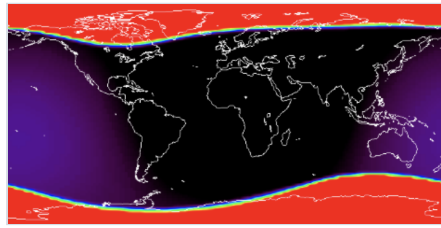
Ozone trends by altitude: recovery in the upper stratosphere, increasing depletion higher up.

5d. Five pathways and how fast they act

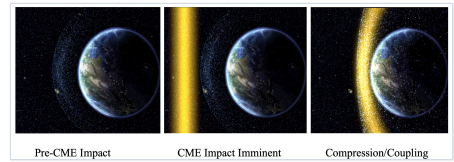
Solar input	How it gets in	Speed
X-ray flares	Ionize the upper atmosphere and ionosphere, changing conductivity worldwide through the ionospheric waveguide	Minute scale
Solar protons	Flares and CMEs accelerate protons along the magnetic field to the polar cusps, ionizing the polar upper atmosphere	Minutes after the flare
Solar wind	CME and coronal-hole streams enter at the polar cusps; aurora; electrons pushed down on the sun side	Fast once it arrives (a CME takes days to get here)
Geomagnetic storms	Magnetic-field swings drive electric currents through the lower atmosphere and the crust	Starts as the storm hits Earth
Cosmic rays	Drive straight down into the atmosphere as particle cascades (they do not need the circuit)	Constant; swings 5-10% or more



Ionization from an X-ray flare (red), spreading around the world in minutes. Image: from the 8th book



Solar protons: ionization lands at the poles (red). Image: from the 8th book



A CME squeezes Earth's magnetic field. Image: from the 8th book

- MeV electrons can jump into the outer radiation belt within minutes. Geomagnetic sudden-commencement electric fields cross the globe at nearly light speed.
- **Lags:** the big modes respond 1-20 years later. Temperature, rain, clouds, wind, lightning, storms and jets can respond in **minutes to hours**.
- Only the polar-heavy proton events stay mostly polar. The other pathways spread worldwide almost at once, on the day side and the night side.

5e. What the climate models leave out

Solar forcing item	Type	In models today?
Irradiance (UV light)	Light	Yes
Flares (X-ray light)	Light	No
Protons	Particles	No
Solar wind	Particles	No
Geomagnetic storms	Magnetism	No
Cosmic rays	Particles	No

- Irradiance is only about **20%** of solar forcing. The parts left out are about **80%**, which is 4 times irradiance alone.
- Models also use a solar "forcing" record that **dips** during big flares (Section 1), so the real surge gets counted as no solar effect.
- Until these pathways and their statistical links are added, climate model forecasts and their blame for climate change cannot be trusted.
- These solar studies were not part of the official climate-change discussion before CMIP6 (the model round that started in 2022).

SECTION 6

Trends and the Climate-Change Question

The big picture: climate has always swung, and sometimes fast. The Sun and the oceans drive those swings. Modern warming is small beside past natural events, CO₂ is plant food, and the temperature record has problems.

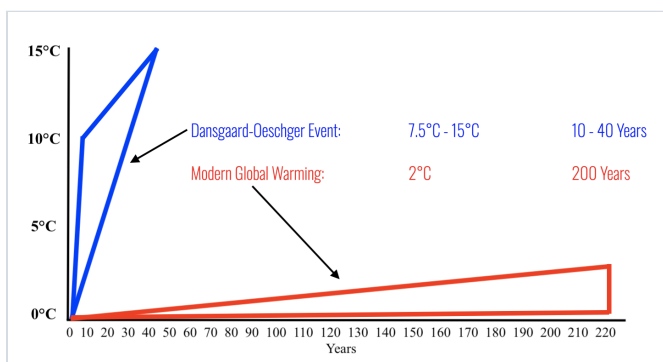
6a. Long swings: grand cycles and the Little Ice Age

Solar cycle	What it is
~22 years (Hale)	Two 11-year cycles make one magnetic cycle; shows up often in climate data
~80-88 years (Gleissberg)	A harmonic of the 11/22-year cycles; clear in radiocarbon data
~200 years	Seen in radiocarbon data
~400-440 years (grand solar cycle)	Long sunspot reconstructions show regular peaks and troughs; the height varies, the spacing does not

- **Little Ice Age:** 1400-1700. It fell in the last **grand solar minimum** (the Maunder Minimum), and it ended when the Maunder Minimum ended, around 1700.
- Solar minima bring: prolonged **negative NAO** phases; cooling in temperature records; abrupt **monsoon failures** in India; drought and flood patterns in Europe and North America; and long **Jamaican droughts** (a southward push of Hadley cells). The usual solar link to the AMO breaks down.
- Cold times bring **crop failures, famine and social stress**. Warm periods favor life.
- Today's grand maximum is the strongest solar activity since the last ice age ended more than 10,000 years ago, and another grand minimum is expected this century.
- **In a grand minimum:** all the big modes are pushed negative, with more cosmic-ray cloud and cooling, and weak circulations, jets and vortices.

6b. Sudden shifts: climate can move fast

- **Dansgaard-Oeschger (D-O) events:** sharp warmings in Greenland and the North Atlantic, up to **15 °C** (mostly 7.5-12 °C), read from ice-core oxygen isotopes.
- Early studies said decades. Newer ice-core data say **within 10 years**; some studies say 1-3 years, and a few say under a year.
- Modern warming of 1-2 °C over a century is not extreme. D-O events made **3x to 15x the change in under 10% of the time**, and they were natural.

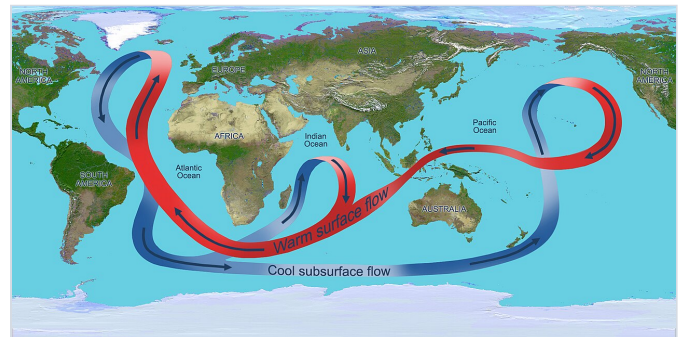


D-O events versus modern warming. Image: from the 8th book

Heating causes cooling: melt freshens the North Atlantic and triggers cold.

Event	When	What happened
Heinrich events	Ice age	Iceberg surges from the Laurentide Ice Sheet melted into the North Atlantic, followed by cooling
Heinrich Event 1	~17,000 years ago	Freshwater weakened ocean circulation and spread sea ice
Younger Dryas	~12,800 years ago	Meltwater reversed warming; North Atlantic region dropped several degrees within decades
8.2 ka event	~8,200 years ago	An ice-dammed lake drained into the Labrador Sea; Greenland cooled by over 2 °C for about 160 years

- **How it works:** fresh water is lighter, so cold salty water stops sinking, ocean circulation slows and less heat goes north.
- **Side effects:** tropical rain belts shift south, droughts hit monsoon regions in Africa and Asia, and the south warms in a "bipolar seesaw."
- **AMOC** (Atlantic Meridional Overturning Circulation): the conveyor that carries warm water north and cold water south. It keeps Western Europe mild. It is weakening, and a machine-learning study puts its collapse window at **2040-2065**. (The 2004 film *The Day After Tomorrow* dramatized this.)
- **Beaufort Gyre** (Arctic Ocean): now the largest Arctic freshwater reservoir, with liquid freshwater up about **40%** in two decades. A sudden release (about 0.02 Sv) can cut Labrador Sea salinity by up to about 0.4 and cool the North Atlantic, like the Great Salinity Anomaly of the 1970s. A smaller release in the 1980s freshened the western Labrador Sea.
- **Takeaway:** a cold future.



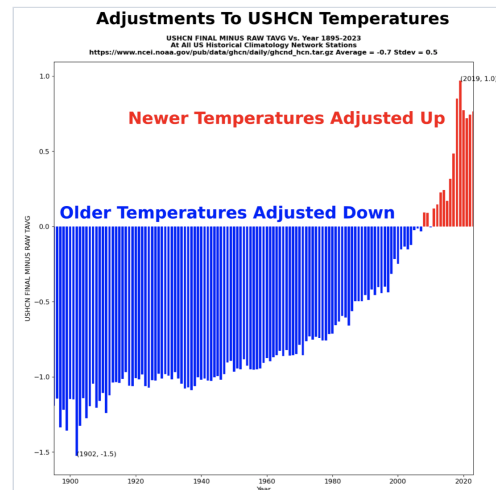
*The global ocean conveyor, with warm surface flow and cool deep flow.
Image: NASA*

6c. CO₂: plant food

- **The evidence:** big warming and cooling swings came before industry; low-sensitivity climate models fit better, so warming to 2100 will be milder than the usual forecasts; CO₂ played a secondary role in past ice-age cycles; statistical artifacts exaggerate CO₂-temperature links; CO₂ has little effect on the thermosphere's temperature.
- **CO₂ is plant food.** Today's level is about **420 ppm**. In the Cambrian and Devonian periods it was above **4,000 ppm**, and in the Mesozoic ("Age of Dinosaurs") about **1,000-2,500 ppm** with a warmer world. Plants have been near starvation for the last 4 million years.
- Below about **150 ppm** most plants struggle; near **100 ppm** photosynthesis stops.
- More CO₂ helps plants save water and raises many crop yields. At 1,000 ppm, about **15%** of today's deserts would stop being plantless.
- Warmer times mean longer growing seasons, less frost damage and more habitat for species.
- **Convergence:** solar forcing was highest in about 11,000 years, volcanic cooling was lowest since the 1500s, and a weakening magnetic field lets in more solar particles, all during the modern warming.

6d. Can we trust the thermometers?

- **"Ghost stations":** NOAA weather stations that were shut down still have temperature values, marked "E" for estimated (examples: Everglades, Florida, and Cambridge City, Indiana). The numbers are filled in from nearby stations, not measured. Meteorologist John Shewchuk found that up to nearly half of US data is estimated this way.
- **Urban heat island:** cities run warmer from lost trees, heat-trapping streets and buildings, and waste heat. Night temperatures stay high in heat waves. City stations are used to fill in rural ones, which spreads false warming.
- **Adjustments:** agencies adjust records for station moves, new instruments, changed observation times and city growth. Tony Heller's charts show the adjustments cool the past and warm the present, so the 1920s and 1930s look as warm as today in the raw records. Example: Texas 1921, a notably hot year, was adjusted cooler. Raw, unadjusted data should be open to the public.



US temperature adjustments: older years adjusted down, newer years adjusted up. Image: from the 8th book

Bottom line: modern warming is not extreme; CO2 does not dominate; the temperature data have problems; and heating triggers cooling.

The One-Page Master Cheat Sheet

Plain rule: active Sun = steadier weather, positive modes, warmer north, fewer cosmic rays. **Quiet Sun** = blocking, negative modes, cold outbreaks, more cosmic rays. The sun nudges natural cycles; it does not override them. Details are in Sections 1 to 5.

A. Active Sun versus Quiet Sun

What	Active Sun (sunspot max)	Quiet Sun (sunspot min)
Sun and cosmic rays	Many flares and CMEs; fewer cosmic rays	Few flares; CMEs at only 1-10% as many; more cosmic rays
Jets, polar vortex	Flat, fast, stable; strong vortex	Wavy, blocked; vortex breaks
Hadley / Walker	Expand, strengthen	Contract, slow
ENSO	El Niño-like	La Niña-like
NAO, NAM, SAM	Positive: milder, wetter Europe; strong westerlies	Negative: cold, blocked, more storms south
PDO, AMO	Positive: stormy US West Coast; warm Atlantic, more hurricanes	Negative: western US drought; cool Atlantic, fewer hurricanes
Temperature	Northern Hemisphere warmer; milder winters in Europe, eastern North America	Cooler; harsher winters; long minima cool (Maunder Minimum)
Rain	No global rule. It depends on region and on which mode is in play (see B).	
Clouds, lightning	Fewer cloud seeds; less lightning	More cloud seeds; more lightning
Storms	Tracks run poleward; fewer cold outbreaks	Tracks shift toward the equator; more typhoons in the western Pacific
Lag	Storms, clouds, pressure and wind: minutes to hours. Big modes: about 1-4 years (ENSO, NAO), decades (PDO, AMO).	

B. Where you feel it

Region	Quick note
Europe, eastern US	Active: milder winters (positive NAO). Quiet: harsh, snowy winters and blocking.
Pacific Northwest, Prairies, Midwest	Active: drier and warmer. Quiet: colder and stormier.
Southwest US, Caribbean	Long droughts line up with low solar activity.
Australia	Positive SAM (active Sun): warmer. Quiet Sun: colder and stormier.
India, East Asia	Monsoons follow the solar cycle; failures at grand minima.
Brazil	High solar activity goes with less rain.

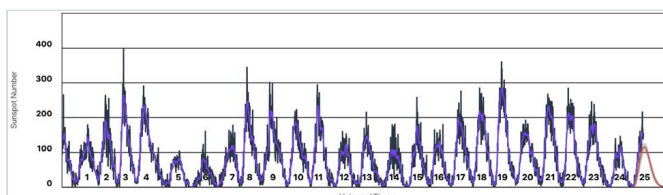
C. Ten quick rules

1. Sunlight (TSI) is the Sun's smallest swing, only ~0.1%.
2. The bigger swings are X-rays, particles, magnetism and cosmic rays.
3. Active Sun means fewer cosmic rays; quiet Sun means more.
4. Active Sun means positive modes and steady weather.
5. Quiet Sun means blocking, negative modes and cold or flood extremes.
6. Modes lag the Sun by about 1-4 years; storms respond in hours.
7. Use geomagnetic activity, not sunspots, for timing. It peaks 1-3 years after sunspot maximum.
8. Sudden jumps after quiet spells matter more than raw size.
9. Regional answers differ. No single rule fits rain or hurricanes.
10. Models leave out the particle side (about 80%).

D. Forecaster's five questions

1. What phase is the sunspot cycle in?
2. How strong was the last cycle, and how long and low was the last minimum?
3. Is solar wind or geomagnetic activity high right now?
4. Which phase are ENSO and NAO in?
5. What season and region?

Line up the timing: when solar and natural cycles match, results are strongest. When they do not, expect a low-confidence forecast.



Sunspot cycles 1-25: each cycle has a different height. Image: from the 8th book

E. After a big flare and CME

When	What to expect
Minutes	X-rays ionize the upper air and boost the global electric circuit; protons start changing polar pressure.
Flare in daylight with storms	Sun-facing tropical storms intensify, and favor east-west tracks.
CME hits (days later)	Sun-facing pressure cells strengthen; cloud and cosmic-ray ionization drop (Forbush decrease); NAO trends positive for up to nine days.
Geomagnetic storm	Existing storms strengthen; sudden stratospheric warmings and fewer jet blocks are more likely; a short burst of lightning, hail or tornadoes in storms hit by electron injection.

F. Glossary: 12 terms

TSI	Total sunlight reaching Earth (~1361 W/m ²)	Hadley / Walker cells	Tropical air loops, north-south and east-west
Forcing	A push that changes the climate	Jet stream	Fast wind river high in the air
Sunspot cycle	~11-year rise and fall of sunspots	Polar vortex	Winter pool of cold polar air
Solar wind	Charged particles streaming from the Sun	ENSO	El Niño / La Niña Pacific swings
Cosmic rays	Fast particles from deep space	NAO	Icelandic Low vs Azores High seesaw
Geomagnetic activity	Shaking of Earth's magnetic field	GEC	Global electric circuit, ionosphere to ground