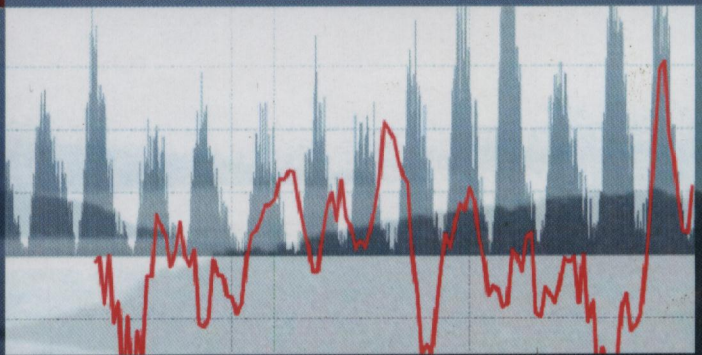


# Solar Activity and Earth's Climate

Rasmus E. Benestad



Second Edition





# Contents

|  |      |
|--|------|
| Preface to the second edition . . . . .              | xi   |
| Preface to the first edition . . . . .               | xiii |
| Acknowledgements to the second edition . . . . .     | xv   |
| Acknowledgements to the first edition . . . . .      | xvii |
| List of figures . . . . .                            | xix  |
| List of tables . . . . .                             | xxv  |
| <b>1 Introduction</b> . . . . .                      | 1    |
| 1.1 The philosophy of this book . . . . .            | 1    |
| 1.2 The layout . . . . .                             | 5    |
| <b>2 Solar observations</b> . . . . .                | 7    |
| 2.1 Synopsis . . . . .                               | 7    |
| 2.2 Instruments for observing the Sun . . . . .      | 7    |
| 2.2.1 Measuring the total solar irradiance . . . . . | 8    |
| 2.2.2 There is more than total irradiance . . . . .  | 8    |
| 2.2.3 Spectrography and polarisation . . . . .       | 10   |
| 2.3 The history of solar observations . . . . .      | 12   |
| 2.3.1 The importance of good observations . . . . .  | 14   |
| 2.3.2 Criteria for good observations . . . . .       | 14   |
| 2.4 Palaeo records of solar activity . . . . .       | 17   |
| 2.4.1 Isotopic records . . . . .                     | 17   |
| 2.4.2 Geomagnetic field measurements . . . . .       | 24   |
| 2.5 Space-borne solar observations . . . . .         | 25   |

|          |  |    |
|----------|--|----|
| <b>3</b> | <b>The physical properties of the Sun</b> . . . . .            | 29 |
| 3.1      | Synopsis . . . . .   | 29 |
| 3.2      | The Sun as a star . . . . .                                    | 29 |
| 3.2.1    | Solar size and mass . . . . .                                  | 29 |
| 3.2.2    | The solar rotation . . . . .                                   | 30 |
| 3.2.3    | The solar material . . . . .                                   | 31 |
| 3.2.4    | The Sun's core . . . . .                                       | 31 |
| 3.2.5    | The photosphere . . . . .                                      | 34 |
| 3.2.6    | The chromosphere . . . . .                                     | 38 |
| 3.2.7    | The corona . . . . .   | 38 |
| 3.2.8    | The solar wind . . . . .                                       | 39 |
| 3.3      | The general solar magnetic field . . . . .                     | 40 |
| 3.3.1    | The decay of magnetic fields . . . . .                         | 40 |
| 3.3.2    | The geomagnetic-based solar model . . . . .                    | 41 |
| <b>4</b> | <b>Solar activity</b> . . . . .                                | 45 |
| 4.1      | Synopsis . . . . .   | 45 |
| 4.2      | The umbra . . . . .  | 48 |
| 4.3      | The penumbra . . . . .   | 49 |
| 4.4      | Sunspot groups . . . . .                                       | 50 |
| 4.4.1    | Sunspot brightness and temperature . . . . .                   | 53 |
| 4.5      | Sunspot models . . . . .                                       | 54 |
| 4.5.1    | Dynamo action and magnetism . . . . .                          | 54 |
| 4.5.2    | Convective and hydrodynamical sunspot models . . . . .         | 58 |
| 4.5.3    | Magnetic cooling models . . . . .                              | 58 |
| 4.6      | Solar activity and preferred timescales . . . . .              | 60 |
| 4.6.1    | Solar activity and the sunspot cycle . . . . .                 | 60 |
| 4.6.2    | Spectral analysis . . . . .                                    | 62 |
| 4.6.3    | Wavelet analysis . . . . .                                     | 64 |
| 4.6.4    | Comparison between preferred timescales . . . . .              | 68 |
| 4.7      | Sunspot groups and their magnetic field . . . . .              | 69 |
| 4.7.1    | Alternative measures of solar activity . . . . .               | 70 |
| 4.7.2    | Observed east–west asymmetry in sunspot statistics . . . . .   | 70 |
| 4.8      | The sunspot cycle and total radiance . . . . .                 | 72 |
| 4.8.1    | Sunspots and the solar irradiation . . . . .                   | 74 |
| 4.8.2    | Sunspot-irradiance models . . . . .                            | 75 |
| 4.8.3    | Prediction of sunspots . . . . .                               | 83 |
| 4.9      | Flares, prominences, faculae, and corpuscular clouds . . . . . | 86 |
| 4.9.1    | Flares . . . . .   | 86 |
| 4.9.2    | Prominences . . . . .  | 86 |
| 4.9.3    | Faculae . . . . .  | 86 |
| 4.9.4    | Corpuscular clouds . . . . .                                   | 87 |
| 4.9.5    | Solar brightening, sunspots and faculae . . . . .              | 87 |
| <b>5</b> | <b>Earth's climate</b> . . . . .                               | 89 |
| 5.1      | Synopsis . . . . .   | 89 |



|          |   |            |
|----------|---|------------|
| 5.2      | The observation of Earth's climate                                  | 91         |
| 5.2.1    | Instrumental data   | 91         |
| 5.2.2    | Upper air data  | 99         |
| 5.2.3    | Earth-observing satellites and space-borne UV measurements          | 99         |
| 5.2.4    | Observation of planetary atmospheres                                | 106        |
| 5.2.5    | Palaeo data – “proxy data”  | 106        |
| 5.2.6    | Climate observations  | 109        |
| 5.3      | Basic climate physics   | 110        |
| 5.3.1    | Mass conservation   | 110        |
| 5.3.2    | Energy conservation   | 111        |
| 5.3.3    | Momentum conservation   | 114        |
| 5.3.4    | Effects of Earth's rotation   | 115        |
| 5.3.5    | Charge conservation   | 116        |
| 5.4      | Earth's energy budget   | 117        |
| 5.4.1    | Variations in solar output and terrestrial temperature              | 117        |
| 5.4.2    | Variation in insolation   | 119        |
| 5.4.3    | The natural greenhouse effect                                       | 120        |
| 5.5      | The basic components of Earth's climate                             | 122        |
| 5.5.1    | The atmosphere  | 122        |
| 5.5.2    | The oceans  | 130        |
| 5.5.3    | The cryosphere  | 135        |
| 5.5.4    | The biosphere   | 139        |
| 5.6      | Feedback mechanisms   | 140        |
| 5.6.1    | Stefan–Boltzmann feedback   | 141        |
| 5.6.2    | Water vapour feedback   | 142        |
| 5.6.3    | Ice- and snow-albedo feedback                                       | 143        |
| 5.6.4    | Cloud feedback  | 144        |
| 5.6.5    | Biochemical feedback  | 145        |
| 5.7      | The other planets in our solar system                               | 145        |
| 5.7.1    | The signature of solar variability from other planets               | 145        |
| <b>6</b> | <b>Solar activity and the stratosphere</b>                          | <b>149</b> |
| 6.1      | Synopsis  | 149        |
| 6.2      | Solar activity and UV emission                                      | 150        |
| 6.3      | The role of stratospheric ozone                                     | 151        |
| 6.3.1    | Chemical reactions  | 151        |
| 6.4      | The “ozone hole”  | 153        |
| 6.4.1    | The theory of a link between solar activity and stratospheric ozone | 153        |
| 6.5      | The theory of a link between the QBO and solar activity             | 157        |
| 6.5.1    | Introduction  | 157        |
| 6.5.2    | Sunspots and the QBO  | 157        |
| 6.6      | The theory of a link between the AO and solar activity              | 159        |
| 6.6.1    | Introduction  | 159        |



|          |   |            |
|----------|---|------------|
| 6.6.2    | A connection between solar activity and the AO            | 159        |
| 6.7      | Criticism of solar-stratosphere hypotheses                | 160        |
| 6.8      | Volcanoes   | 161        |
| <b>7</b> | <b>Solar magnetism and Earth's climate</b>                | <b>165</b> |
| 7.1      | Synopsis  | 165        |
| 7.2      | Northern lights and the solar cycle                       | 166        |
| 7.2.1    | Introduction  | 166        |
| 7.3      | Earth's magnetic and electric fields                      | 166        |
| 7.3.1    | Geomagnetic storms  | 166        |
| 7.3.2    | The geomagnetic field and solar wind                      | 167        |
| 7.3.3    | The magnetic field of other planets                       | 168        |
| 7.3.4    | The Van Allen belts                                       | 168        |
| 7.4      | Charging mechanisms                                       | 168        |
| 7.4.1    | Lightning   | 168        |
| 7.4.2    | The atmospheric electric field                            | 168        |
| 7.4.3    | Cosmic rays   | 169        |
| 7.4.4    | Interaction between cosmic rays and the air               | 169        |
| 7.5      | Airglow, sprites and elves                                | 170        |
| 7.6      | A historical note on the aurora: theory and observations  | 171        |
| 7.6.1    | Early scientific documentation                            | 171        |
| 7.6.2    | The aurora and geomagnetic disturbances                   | 171        |
| 7.6.3    | The discovery of day-side and night-side auroras          | 172        |
| 7.6.4    | Charged particles and the aurora                          | 172        |
| 7.6.5    | The northern lights and the weather                       | 172        |
| 7.6.6    | The interplanetary magnetic field and the solar cycle     | 172        |
| 7.7      | The aurora and solar activity                             | 173        |
| 7.7.1    | The theory of day-side auroras                            | 173        |
| 7.7.2    | The theory of night-side auroras                          | 173        |
| 7.7.3    | The aurora and the geomagnetic field                      | 173        |
| 7.7.4    | Aurora activity   | 175        |
| 7.8      | Historical climate information from aurora observations   | 176        |
| 7.8.1    | Aurora and the Maunder minimum                            | 176        |
| 7.8.2    | The "Little Ice Age" and aurora activity                  | 176        |
| 7.8.3    | The magnitude and extent of the "Little Ice Age"          | 177        |
| 7.9      | The Maunder minimum and the quiet-Sun theory              | 177        |
| 7.10     | Magnetic fields, cosmic rays and cloud cover              | 179        |
| 7.10.1   | The cosmic ray and sulphate hypothesis                    | 179        |
| 7.10.2   | The electro-freezing hypothesis                           | 179        |
| 7.10.3   | The galactic cosmic rays and the climate                  | 180        |
| 7.10.4   | Low and high clouds                                       | 180        |
| 7.10.5   | The hypothesis on cosmic rays and cloud droplet formation | 182        |
| 7.10.6   | Criticism of Svensmark's hypothesis                       | 186        |
| 7.11     | The Maunder minimum                                       | 191        |



|          |  |            |
|----------|--|------------|
| 6.6.2    | A connection between solar activity and the AO . . . . .               | 159        |
| 6.7      | Criticism of solar-stratosphere hypotheses . . . . .                   | 160        |
| 6.8      | Volcanoes . . . . .  | 161        |
| <b>7</b> | <b>Solar magnetism and Earth's climate . . . . .</b>                   | <b>165</b> |
| 7.1      | Synopsis . . . . .   | 165        |
| 7.2      | Northern lights and the solar cycle . . . . .                          | 166        |
| 7.2.1    | Introduction . . . . .   | 166        |
| 7.3      | Earth's magnetic and electric fields . . . . .                         | 166        |
| 7.3.1    | Geomagnetic storms . . . . .   | 166        |
| 7.3.2    | The geomagnetic field and solar wind . . . . .                         | 167        |
| 7.3.3    | The magnetic field of other planets . . . . .                          | 168        |
| 7.3.4    | The Van Allen belts . . . . .  | 168        |
| 7.4      | Charging mechanisms . . . . .  | 168        |
| 7.4.1    | Lightning . . . . .  | 168        |
| 7.4.2    | The atmospheric electric field . . . . .                               | 168        |
| 7.4.3    | Cosmic rays . . . . .  | 169        |
| 7.4.4    | Interaction between cosmic rays and the air . . . . .                  | 169        |
| 7.5      | Airglow, sprites and elves . . . . .                                   | 170        |
| 7.6      | A historical note on the aurora: theory and observations . . . . .     | 171        |
| 7.6.1    | Early scientific documentation . . . . .                               | 171        |
| 7.6.2    | The aurora and geomagnetic disturbances . . . . .                      | 171        |
| 7.6.3    | The discovery of day-side and night-side auroras . . . . .             | 172        |
| 7.6.4    | Charged particles and the aurora . . . . .                             | 172        |
| 7.6.5    | The northern lights and the weather . . . . .                          | 172        |
| 7.6.6    | The interplanetary magnetic field and the solar cycle . . . . .        | 172        |
| 7.7      | The aurora and solar activity . . . . .                                | 173        |
| 7.7.1    | The theory of day-side auroras . . . . .                               | 173        |
| 7.7.2    | The theory of night-side auroras . . . . .                             | 173        |
| 7.7.3    | The aurora and the geomagnetic field . . . . .                         | 173        |
| 7.7.4    | Aurora activity . . . . .  | 175        |
| 7.8      | Historical climate information from aurora observations . . . . .      | 176        |
| 7.8.1    | Aurora and the Maunder minimum . . . . .                               | 176        |
| 7.8.2    | The "Little Ice Age" and aurora activity . . . . .                     | 176        |
| 7.8.3    | The magnitude and extent of the "Little Ice Age" . . . . .             | 177        |
| 7.9      | The Maunder minimum and the quiet-Sun theory . . . . .                 | 177        |
| 7.10     | Magnetic fields, cosmic rays and cloud cover . . . . .                 | 179        |
| 7.10.1   | The cosmic ray and sulphate hypothesis . . . . .                       | 179        |
| 7.10.2   | The electro-freezing hypothesis . . . . .                              | 179        |
| 7.10.3   | The galactic cosmic rays and the climate . . . . .                     | 180        |
| 7.10.4   | Low and high clouds . . . . .  | 180        |
| 7.10.5   | The hypothesis on cosmic rays and cloud droplet<br>formation . . . . . | 182        |
| 7.10.6   | Criticism of Svensmark's hypothesis . . . . .                          | 186        |
| 7.11     | The Maunder minimum . . . . .  | 191        |



|          |   |            |
|----------|---|------------|
| 7.11.1   | The weakness of comparisons with “Sun-like” stars . . . . .                             | 193        |
| 7.12     | The influence of corpuscular clouds . . . . .   | 194        |
| 7.12.1   | Solar activity and lightning . . . . .  | 195        |
| 7.12.2   | The geomagnetic field and oceanic currents . . . . .                                    | 196        |
| 7.12.3   | The geomagnetic field and sea level pressure . . . . .                                  | 196        |
| <b>8</b> | <b>A review of solar–terrestrial studies . . . . .</b>                                  | <b>197</b> |
| 8.1      | Synopsis . . . . .  | 197        |
| 8.2      | A brief historical note on solar–terrestrial links . . . . .                            | 199        |
| 8.2.1    | Historical account of sunspots and hypothesised links<br>with Earth’s climate . . . . . | 199        |
| 8.3      | Recent statistics on solar–terrestrial links . . . . .                                  | 208        |
| 8.3.1    | A renaissance for solar–terrestrial links . . . . .                                     | 208        |
| 8.4      | Recent work and hypotheses . . . . .  | 209        |
| 8.4.1    | Basic statistical concepts . . . . .  | 209        |
| 8.4.2    | Linear trends . . . . .   | 212        |
| 8.4.3    | Correlation . . . . .   | 213        |
| 8.4.4    | Correlation and de-trending the data . . . . .  | 215        |
| 8.4.5    | Correlation and filtering the data . . . . .  | 216        |
| 8.4.6    | Autocorrelation and lag-correlation . . . . .   | 220        |
| 8.4.7    | Monte Carlo simulations . . . . .   | 223        |
| 8.4.8    | The solar cycle length and terrestrial temperature . . . . .                            | 226        |
| 8.4.9    | Considerations on solar cycle lengths . . . . .   | 230        |
| 8.4.10   | Correlation studies and pitfalls . . . . .  | 232        |
| 8.5      | Validation of predictions . . . . .   | 234        |
| 8.6      | Total solar irradiance studies . . . . .  | 240        |
| 8.6.1    | The “Little Ice Age” and TSI . . . . .  | 240        |
| 8.7      | Comparisons with stellar studies . . . . .  | 245        |
| 8.7.1    | The life cycle of a star . . . . .  | 245        |
| 8.7.2    | Inferring the solar evolution from stellar studies . . . . .                            | 246        |
| 8.7.3    | The “snowball Earth” effect . . . . .   | 247        |
| 8.8      | Is there a relation between sunspots and rainfall? . . . . .                            | 248        |
| 8.9      | Requirements of solar–terrestrial hypotheses . . . . .                                  | 248        |
| <b>9</b> | <b>Solar activity and regional climate variations . . . . .</b>                         | <b>251</b> |
| 9.1      | Synopsis . . . . .  | 251        |
| 9.2      | El Niño Southern Oscillation and solar activity . . . . .                               | 252        |
| 9.2.1    | How solar activity may physically affect ENSO . . . . .                                 | 260        |
| 9.3      | The role of solar activity in the south Asian monsoon system . . . . .                  | 265        |
| 9.3.1    | The monsoon . . . . .   | 265        |
| 9.3.2    | Relation to sunspots . . . . .  | 266        |
| 9.4      | The North Atlantic Oscillation and sunspots . . . . .                                   | 266        |
| 9.4.1    | How may the NAO be affected by solar activity? . . . . .                                | 267        |
| 9.5      | The Gulf Stream and sunspots . . . . .  | 269        |
| 9.6      | Pacific Decadal Oscillation and solar activity . . . . .                                | 271        |
| 9.7      | Land–sea contrasts . . . . .  | 273        |

|     |           |  |            |
|-----|-----------|--|------------|
| 193 | 9.8       | Other external climate forcings . . . . .                              | 274        |
| 194 | 9.8.1     | The anthropogenic perturbation to the natural balance . . . . .        | 274        |
| 195 | 9.8.2     | Orbital parameters . . . . .   | 275        |
| 196 | 9.8.3     | The Moon . . . . .   | 276        |
| 197 | 9.8.4     | Meteorite impacts . . . . .  | 276        |
|     | <b>10</b> | <b>Synthesis . . . . .</b>   | <b>277</b> |
|     | <b>11</b> | <b>Appendix . . . . .</b>  | <b>281</b> |
|     |           | <b>Bibliography . . . . .</b>  | <b>285</b> |
|     |           | <b>Exercises . . . . .</b>   | <b>299</b> |
|     |           | <b>Index . . . . .</b>   | <b>309</b> |
| 209 | 8.4       | Recent work and hypotheses . . . . .                                   | 8.4        |
| 209 | 8.4.1     | Basic statistical concepts . . . . .                                   | 8.4.1      |
| 212 | 8.4.2     | Linear trends . . . . .  | 8.4.2      |
| 213 | 8.4.3     | Correlation . . . . .  | 8.4.3      |
| 215 | 8.4.4     | Correlation and de-trending the data . . . . .                         | 8.4.4      |
| 216 | 8.4.5     | Correlation and filtering the data . . . . .                           | 8.4.5      |
| 230 | 8.4.6     | Autocorrelation and its correlation . . . . .                          | 8.4.6      |
| 232 | 8.4.7     | Monte Carlo simulations . . . . .                                      | 8.4.7      |
| 236 | 8.4.8     | The solar cycle length and terrestrial temperature . . . . .           | 8.4.8      |
| 239 | 8.4.9     | Considerations on solar cycle lengths . . . . .                        | 8.4.9      |
| 232 | 8.4.10    | Correlation studies and pitfalls . . . . .                             | 8.4.10     |
| 234 | 8.5       | Validation of predictions . . . . .                                    | 8.5        |
| 240 | 8.6       | Total solar irradiance studies . . . . .                               | 8.6        |
| 240 | 8.6.1     | The "little ice Age" and TSI . . . . .                                 | 8.6.1      |
| 245 | 8.7       | Comparison with solar studies . . . . .                                | 8.7        |
| 245 | 8.7.1     | The life cycle of a star . . . . .                                     | 8.7.1      |
| 246 | 8.7.2     | Inferring the solar evolution from stellar studies . . . . .           | 8.7.2      |
| 247 | 8.7.3     | The "snowball Earth" effect . . . . .                                  | 8.7.3      |
| 248 | 8.8       | Is there a relation between sunspots and rainfall? . . . . .           | 8.8        |
| 248 | 8.9       | Requirements of solar-terrestrial hypotheses . . . . .                 | 8.9        |
| 251 | 9.1       | Solar activity and regional climate variations . . . . .               | 9.1        |
| 251 | 9.1       | Synopsis . . . . .   | 9.1        |
| 252 | 9.2       | El Niño Southern Oscillation and solar activity . . . . .              | 9.2        |
| 260 | 9.2.1     | How solar activity may physically affect ENSO . . . . .                | 9.2.1      |
| 265 | 9.2.2     | The role of solar activity in the south Asian monsoon system . . . . . | 9.2.2      |
| 265 | 9.2.3     | The monsoon . . . . .  | 9.2.3      |
| 266 | 9.2.4     | Relation to sunspot cycles . . . . .                                   | 9.2.4      |
| 266 | 9.3       | The North Atlantic Oscillation and sunspots . . . . .                  | 9.3        |
| 267 | 9.3.1     | How may the NAO be affected by solar activity? . . . . .               | 9.3.1      |
| 268 | 9.4       | The Gulf Stream and sunspots . . . . .                                 | 9.4        |
| 271 | 9.5       | Pacific Decadal Oscillation and solar activity . . . . .               | 9.5        |
| 273 | 9.6       | Land-sea contrasts . . . . .   | 9.6        |



## DO SUNSPOTS AFFECT OUR CLIMATE?

This question has been a focus of scientific debate since the existence of sunspots was established in the early 17th century. Even today, however, the answer is not forthcoming; while there are valid reasons to believe that solar activity has some impact on the Earth's climate, the history of the subject shows that there have been many unsupported statements that over-estimate the effect of sunspots on climatic variations.

This updated and revised edition of *Solar Activity and Earth's Climate* introduces the reader to the subject of solar activity and the connection with the Earth's climate. It focuses on how knowledge about the solar cycle and Earth's climate is obtained, and provides an in-depth discussion of observations, methods and the physics involved, together with the necessary statistics and analysis.

ISBN 3-540-30620-X

