

Clouds, circulation and climate sensitivity

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1 Clouds, Circulation and Climate Sensitivity

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18 **Fundamental puzzles of climate science, such as our inability to provide robust as-**
19 **sessments of future global and regional climate changes, are rooted in our limited**
20 **understanding of how clouds, circulation and climate interact. Recent advances in**
21 **our capacity to observe, simulate and conceptualize the climate system now make it**
22 **possible to improve this understanding. We argue that by focussing research on a**
23 **handful of important scientific questions, particularly those that have become more**
24 **tractable as a result of recent advances, will accelerate progress. Four such questions**
25 **are outlined below. They aim at understanding the role of cloud feedbacks and con-**
26 **vective organization in climate, and the factors that control the position, the strength**
27 **and the variability of the tropical rain belts and the extra-tropical storm tracks.**

28 Clouds stimulate the human spirit. Recognised for centuries as harbingers of weather,
29 only in recent decades have scientists begun to appreciate their role in determining the gen-
30 eral circulation of the atmosphere and its susceptibility to change.

31 Forming mostly in the updrafts of the turbulent and chaotic air-flow, clouds em-
32 body the complex and multi-scale organisation of the atmosphere into dynamical entities,
33 or storms. These entities are responsible for mediating the radiative transfer of energy,
34 distributing precipitation, and are often associated with extreme winds. It has long been
35 recognized that water and the diabatic processes it mediates play a fundamental role in
36 tropical circulations, and there is increasing evidence that they also influence extra-tropical
37 circulations¹. Globally, the impact of clouds on Earth's radiation budget and hence surface
38 temperatures, also depends critically on how clouds interact with one another and with
39 larger scale circulations². Far from being passive tracers of a turbulent atmosphere, clouds
40 thus embody processes that can actively control circulation and climate (Box 1).

41 For practical reasons, early endeavours to understand climate deployed a divide and
42 conquer strategy in which efforts to understand clouds and convective processes developed
43 separately from efforts to understand larger-scale circulations. Over time, a gap developed
44 between the sub-disciplines. However, technological progress and conceptual advances
45 have tremendously increased our capacity to observe and simulate the climate system, such
46 that it is now possible to study more readily how small-scale convective processes — that
47 is, clouds — couple to large-scale circulations (see Box 2). Much like a new accelerator
48 allows physicists to explore the implication of the interactions among forces acting over
49 different length scales, these new capabilities are transforming how atmospheric scientists
50 think about the interplay of clouds and climate. This offers a great opportunity not only to
51 close the gap between scientific communities, but also to answer some of the most pressing
52 questions about the fate of our planet.

53 **Urgent need for accelerated progress**

54 Climate is changing at an unprecedented pace³. Government and private decision makers
55 involved in planning and risk assessments urgently need information about how rapidly
56 temperatures will rise, how rainfall patterns will change, and whether the frequency of ex-
57 treme weather will increase. Climate scientists have built a successful research framework
58 for detecting and attributing some global aspects of climate change, such as the basic
59 trends in globally averaged temperatures and sea level. This success is reflected in the
60 growing level of confidence in understanding of such changes³. However this framework
61 is much less effective when it comes to quantifying critical aspects of climate change such
62 as the climate sensitivity or regional changes. On these aspects, observational data sets are
63 limited, natural variability obscures the anthropogenic signal, and climate models produce
64 uncertain projections^{4,5}. This leads to a low confidence in their assessment³.

65 A deeper understanding of how clouds and aerosols affect the planetary energy bud-
66 get is needed if we are to increase our confidence in these fundamental aspects of cli-
67 mate change^{6,7}. However, given the strong dependence of regional climate patterns and
68 extremes on the large-scale circulation, it is equally important to better understand how
69 clouds and convection affect atmospheric dynamics and its change as the troposphere be-
70 comes warmer and wetter, the stratosphere colder and the cryosphere smaller^{4,8} (Box 1).
71 Our degree of understanding of the interplay between clouds, circulation and climate sen-
72 sitivity thus demarcates the frontiers of our ability to anticipate climate changes.

73 Numerical models have always played an important role in climate change studies
74 and assessments. However, robust conclusions require more than a consensus by the most
75 comprehensive models. They require the underpinning of physical arguments –theories–
76 developed through the use of a hierarchy of models and critically assessed using available
77 data^{6,9}. An increased emphasis on *understanding* may well be the best course of action to
78 develop reliable insights about climate change, but also to address their urgent need. Con-

79 conceptual breakthroughs have typically come from rephrasing old questions in a new way,
80 one that makes long-standing problems finally tractable. Advances in key issues such as
81 the extent of the Hadley cell¹⁰, the intensity of tropical cyclones¹¹, or the height reached
82 by convective clouds¹², have all come through idealized studies and clever application of
83 physical reasoning to obtain constraints on the system, leading to new ways of using and
84 interpreting comprehensive models, and linking them to observations. We argue therefore
85 that accelerating progress in climate change assessments requires an approach focused on
86 the development and testing of hypotheses that link changes in regional patterns, extremes,
87 climate sensitivity, and other important features of climate in a self-consistent way. The
88 theories or 'story lines' that emerge from such an approach emphasize physical concepts
89 and testable ideas around which scientific activity can organise, and may also make com-
90 munication of risk-based assessments more concrete.

91 By focusing the development of story lines around a few carefully chosen questions,
92 a more comprehensive analysis will be possible, one in which the integration of obser-
93 vations, evidence obtained from a hierarchy of models, and physical understanding will
94 advance knowledge much more efficiently than would the consideration of particular lines
95 of evidence in isolation. Below, four such questions are outlined. Among the great variety
96 of questions one might consider, these four stood out both because of their centrality to a
97 more specific understanding of global and regional climate changes, and because new and
98 emerging approaches or insights are, as outlined below, making them more tractable.

99 **Four Questions**

100 *** What role does convection play in cloud feedbacks?**

101 Many changes of the climate system at global and regional scales are mainly deter-
102 mined by the globally averaged temperature. For this reason, one of the simplest and most
103 important measures of the system response to forcing remains the "climate sensitivity",

104 i.e., the equilibrium change in the globally averaged near-surface temperature in response
105 to a doubling of the concentration of atmospheric CO₂. Available evidence suggests a
106 range in the climate sensitivity from 1.5 to 4.5 K³. The socio-economic implications of
107 this uncertainty are enormous — a simple calculation demonstrates that to maintain a
108 warming target of two degrees, nearly twice as much CO₂ could be emitted in a low (1.5
109 K) climate sensitivity world as compared to a high (4.5 K) sensitivity world. Economic
110 modelling suggests that progress in the assessment of climate sensitivity would have a
111 staggering economic value¹³.

112 Although the likely range of climate sensitivity estimates has not narrowed in the
113 past three decades, tremendous progress has been made in understanding the factors con-
114 trolling climate sensitivity^{6,7}. It is now possible to delineate between well understood
115 processes, which contribute to a base value of about 2.7 K¹⁴, from more poorly understood
116 processes – largely cloud feedbacks.

117 Cloud feedbacks could be described as the climate systems equivalent of Winston
118 Churchill's Russia: "a riddle wrapped inside a mystery inside an enigma. Over the past
119 decades at least some aspects of cloud feedbacks have at least become less enigmatic.
120 Mechanisms governing the height of the deepest clouds are now much better understood¹².
121 Feedbacks from clouds in the planetary boundary layer over oceans (Fig. 1), which make
122 one of the largest contributions to inter-model spread in climate sensitivity, appear to
123 be driven largely by mixing of the lower troposphere by shallow convection^{2, 15–17}; in a
124 warmer climate these processes are expected to dry the marine boundary layer over the
125 vast expanse of the tropical oceans, reducing the low-cloud amount and the Earth's albedo
126 in a way that amplifies warming. These and other cloud feedback processes are increas-
127 ingly understood as being mediated by changes in atmospheric circulations rather than by,
128 for example, microphysical effects⁷.

129 This emerging narrative may make cloud feedbacks less enigmatic, but leaves the
130 mystery as to the nature of the interplay between clouds and convection. This riddle is

131 manifest in the tendency of models to exhibit a large degree of freedom in their prediction
132 of upper-level cloud cover responses¹⁸, and in their representation of shallow convective
133 mixing, which appears to determine the strength of their low-cloud feedbacks². Convective
134 mixing processes have been found to be important in explaining the distribution of the
135 tropical rain belts, and may also affect climate (temperature) and hydrological (rainfall)
136 sensitivity through processes currently missing or poorly represented in climate models
137 – for instance convective scale organization, or processes related to the distribution of
138 clouds at mid to upper levels. Might the presently crude representation of convective
139 mixing processes in models be missing important cloud feedback mechanisms?

140 These ideas could be tested by suppressing or altering processes in comprehensive
141 models in ways that are guided by results from observations or more fundamental models.
142 One could then ask to what extent the broader implications of such processes are consis-
143 tent with other things we know. So doing would help explain how much of the model
144 spread can be attributed to differences in convective parameterizations, or whether poor
145 parameterizations (or simply the absence of critical processes) are skewing our prediction
146 of the system. Increasingly specific ideas could also guide the collection and analysis of
147 Earth observations, for instance through field experiments focusing on undisturbed con-
148 ditions in the maritime tropics or improved space based estimates of lower tropospheric
149 water vapour.

150 *** What controls the position, strength and variability of storm tracks?**

151 Extratropical storms draw their energy from the temperature contrast between the
152 equator and poles. They are associated with the familiar high and low pressure systems
153 of the midlatitudes, with their attendant temperature fronts, precipitation, and sometimes
154 severe weather. Most extra-tropical storms develop, organise and decay in spatially lo-
155 calised regions known as “storm tracks.” The storm tracks tend to be roughly aligned with
156 the global jet streams (upper-level eastward wind currents) and are major components of
157 the general circulation through their role in the meridional transport of energy, moisture

158 and momentum, and in the modification of Earth's energy budget through associated pat-
159 terns of clouds (Fig. 2).

160 The jets and the storms interact with each other symbiotically, giving rise to low-
161 frequency variations. One feature of this variability is the emergence of persistent “block-
162 ing” events, which effectively reroute storms away from their usual track. Blocking events
163 can be associated with summer heat waves and winter cold snaps over the blocked region,
164 as well as unusual storminess away from the block. Year to year variability in the position
165 of the storm tracks is associated with large swings in temperature: monthly averaged tem-
166 peratures in the upper mid-west of the United States, for instance, can vary by more than
167 10 °C from one year to the next as the storm tracks shift. Likewise, unusual persistence in
168 the path of successive storms can lead to widespread flooding as was the case for the UK
169 in the winter of 2013/2014, or to unseasonably pleasant weather.

170 The chaotic variations of the storm tracks become manifest as natural weather and
171 climate variability on decadal timescales, which makes it difficult to attribute a change
172 in any given year to changes in the climate. But models and theory do suggest that the
173 storm tracks are sensitive to external forcing, for instance changes in meridional tempera-
174 ture gradients. Near the surface, temperature gradients are expected to weaken as surface
175 warming is stronger near the poles; aloft, temperature gradients will strengthen as the
176 stratosphere cools and the tropical upper troposphere warms. These changes have oppos-
177 ing effects¹⁹, but on balance models suggest that storm tracks will shift poleward with
178 warming. Support for this line of thinking arises from a discernible poleward shift of sum-
179 mertime precipitation in the Southern Hemisphere, which has been attributed to cooling
180 in the polar stratosphere resulting from the depletion of ozone there²⁰. But these shifts
181 are not monolithic, particularly in the Northern Hemisphere where zonal asymmetries are
182 fundamental to an understanding of storm track location²¹. Changes in the zonal asym-
183 metry of the jet can lead to equator-ward shifts in regions²² even if, on average, the jet is
184 displaced poleward.

185 Even for changes in the jets that models robustly simulate, understanding remains
186 low. Uncertainty in future projections is not surprising as models also exhibit large biases
187 in the simulation of the present day, with storm tracks located too far equatorward and, in
188 the Northern Hemisphere, too zonally oriented²³. Progress in developing a narrative for
189 future storm track changes will likely depend on progress in understanding the origins and
190 implications of these biases.

191 Theoretical understanding of extratropical storms is largely based on dry dynamics,
192 but the water that flows through these storms also plays a fundamental role in determining
193 their evolution. Half of the poleward transport of energy within storm tracks is accom-
194 plished by the latent heat component, meaning moisture is vital in setting the temperature
195 gradients upon which storms grow. The release of latent heat within the warm sector of
196 storms and in frontal regions has long been understood as an important and additional
197 energy source for cyclogenesis. However the myriad ways in which clouds couple to the
198 storm tracks are just beginning to be appreciated, for instance through their radiative ef-
199 fects. As the clouds embedded within the storm tracks shift, there are systematic implica-
200 tions for the radiation budget and its influence on the temperature gradients that give rise to
201 the storms in the first place^{24,25}. The development of a hierarchy of modelling approaches
202 is advancing understanding of how moist processes such as those imbedded along frontal
203 systems, interactions with ocean circulations, and cloud radiative effects, influence both
204 storm development and the structure of the storm tracks. Because storm tracks are large
205 enough to be resolved across these model hierarchies, and very high-resolution approaches
206 can also increasingly resolve convective circulations within the storm system²⁶ as well as
207 remote influences from fine-scale orography or changes in tropical circulations, hierarchi-
208 cal modeling approaches hold particular promise for developing story lines of how storm
209 tracks will change in the future.

210 To gain confidence in these emerging story lines, it will be useful to look to the
211 past. Models suggest that storm tracks have responded to past external forcings²⁷. A

212 maturing theoretical understanding of these changes, expressed for instance in the form
213 of hypotheses of storm track change during the last-glacial maximum or mid-holocene
214 periods, could be tested using reconstructions of past precipitation changes from pollen
215 records²⁸. Developing an understanding of storm-track dynamics that would allow us both
216 to explain the record of past changes and to robustly predict the tendency of a change,
217 would be a significant advance.

218 *** What controls the position, strength and variability of the tropical rain belts?**

219 In the tropics, rain tends to be concentrated in compact bands or belts (Fig. 3). Over
220 the ocean, the Inter-tropical Convergence Zone (ITCZ) contains some of the rainiest re-
221 gions on the planet, and some of the deepest cumulonimbus and stratiform anvil clouds.
222 These tropical rain belts are so closely related to the monsoons, which spread the rainy re-
223 gions more poleward over land, that scientists increasingly think of those monsoons as the
224 terrestrial amplification of the seasonal migration of the rain belts. These climate features
225 directly affect hundreds of millions of people, who depend on rainfall for fresh water.

226 Tropical rain belts cannot be understood without understanding the roles of the
227 clouds within them. Over the ocean these rain belts are tied to the warmest sea surface tem-
228 peratures, which favour sustained rising motion as seen in the rising branch of the Hadley
229 and Walker circulations. The high clouds in the rain belts have a strong effect on shortwave
230 radiation due to the amount of condensate, and on long-wave radiation due to their height.
231 These radiative effects influence both sea surface temperature and atmospheric circulation.
232 The breadth of the subsiding branches of tropical over-turning circulations determines the
233 prevalence of low clouds within the broader tropics. Any climate forcing that leads to a
234 change in strength, width, or location of a tropical rain belt is thus potentially associated
235 with a cloud feedback, which will in turn influence the patterns of temperature change and
236 circulation response to the forcing.

237 Local interactions between the atmosphere and the upper ocean or the land surface

238 have long been recognized to play a role in determining the position of the rain belts.
239 However recent work has emphasized that changes in the rain belts' location and intensity
240 are intimately coupled to circulations on a variety of scales. Mesoscale convective circula-
241 tions appear to influence the poleward extent of the monsoon in ways that are just starting
242 to be understood²⁹, and planetary scale circulations connect the rain belts to processes in
243 distant extra-tropical locations³⁰. Newly developed energetic frameworks have proven to
244 be a useful way to understand these connections³¹. Models suggest that high-latitude heat
245 sources, for example, drive atmospheric heat transport through the midlatitudes and into
246 the tropics. There, the Hadley cell responds by transporting energy away from the heating,
247 and moisture toward the heating. This causes tropical rain belts to be displaced toward
248 the heating, even when that heating is located far away. This type of tropical-extratropical
249 interaction may help explain the double-ITCZ problem in climate models, a longstand-
250 ing bias associated with an overly pronounced southern ITCZ: a deficit in cloudiness over
251 the Southern Ocean warms the entire southern hemisphere, causing excessive precipita-
252 tion within the southern tropics and driving a stronger ITCZ in the southern hemisphere³².
253 This process probably explains why cooling in one hemisphere by aerosols or ice sheet
254 expansion pushes the tropical rain bands toward the opposite hemisphere³³.

255 Historical evidence also supports the view that tropical rain bands may be quite
256 mutable. Most strikingly, in the Sahara, vegetation and lake indicators, as well as many
257 examples of rock art, document periods such as the early and mid-Holocene, when the
258 African monsoon extended much further north than today (see Box 2). Although much
259 of this change would seem to be due to changes in insolation driven by precession of
260 Earth's orbit, this factor alone is insufficient to explain the shift in today's climate models,
261 even when vegetation feedbacks are taken into account³⁴. Past ITCZ shifts may be poorly
262 simulated at other time periods as well, e.g., the Last Glacial Maximum³⁵. Insufficient
263 understanding, and uncertainties in past climate reconstructions, make it difficult to assess
264 modelled responses. Hence, developing a story line for future changes in tropical rain
265 bands will be a challenge, one that seems unlikely to be met without coordinated efforts

266 using a hierarchy of models to work through specific hypotheses motivated by more robust
267 evidence of past changes.

268 *** What role does convective aggregation play in climate?**

269 Satellite imagery offers an inexhaustible opportunity to admire the vast variety of
270 ways in which moist convection is organised: from randomly scattered small clouds, to
271 clusters of convective cells forming in arcs, bands or whirls on mesoscales, as well as
272 large-scale cloud systems which trace circulations on the planetary scale. The propensity
273 of convection to aggregate and organise has long been related to the variability of weather
274 and to the occurrence of extreme rainfall events. The idea that the organization of moist
275 convection might play a role in the dynamics of the climate system is not a new one. In-
276 sights from field studies dating to the dawn of the satellite era have suggested that tropical
277 convective clusters affect vertical profiles of atmospheric heating significantly enough to
278 influence circulations on much larger scales³⁶.

279 Idealised numerical studies have led to renewed interest in the subject of organiza-
280 tion. These studies demonstrate that convection can aggregate spontaneously even in the
281 absence of external drivers (Fig. 4), leading to the concept of “self-aggregation”³⁷. These
282 studies, and observational analyses inspired by them, suggest that the degree of aggrega-
283 tion of a given amount of convection influences the mean atmospheric state: an atmosphere
284 in which convection is more aggregated is drier, clearer, and more efficient at radiating
285 heat to space^{37,38}. Cloud-resolving simulations further suggest that self-aggregation might
286 increase with temperature³⁹. If so, convective aggregation could feed back on climate
287 changes driven by other influences, and may contribute to changes in extreme events.

288 The tendency of deep convection to organise may also influence the general atmo-
289 spheric circulation. Because convection often organises in a way that modulates the ener-
290 getics of the atmosphere, the presence of organization on scales of a few tens to several
291 hundreds of kilometers may influence the strength of larger-scale vertical motions and per-

292 haps the structure of the tropical rain belts. Another hypothesis is that long-standing rid-
293 dles, like the Madden-Julian Oscillation (a 30-60 day oscillation of rainfall patterns in the
294 tropical Indo-Pacific region) are a large-scale manifestation of convective self-aggregation.

295 Observations and numerical simulations at very high resolution are showing that
296 the convective organization is also important for the development of precipitation from
297 shallow convection⁴⁰. Such organization buffers the response of clouds to perturbations
298 in the aerosol environment, or changes in surface fluxes. Likewise, because the effects of
299 shallow cloud cover on radiation can help organize deep convection⁴¹ and influence the
300 structure of tropical convergence zones⁴², the organization of convection on a wide range
301 of scales may create an interesting link between the cloud feedback and the tropical rain
302 belt questions.

303 Highly resolved simulations offer opportunities to develop and test an emerging nar-
304 rative on the role of convective organization. By using such very high-resolution ap-
305 proaches to more fundamentally understand the physical processes underlying aggrega-
306 tion, it may be easier to introduce compelling representations of aggregating processes in
307 large-scale models, or disaggregating processes in the highly resolved simulations. Such
308 approaches would enable numerical experiments aimed at assessing whether or not, and if
309 so how, convective aggregation matters for climate. And these experiments can form the
310 basis for improving the design of field experiments, or informing the analysis of existing
311 data, so as to test the story lines that develop from the modelling.

312 **A Grand Challenge**

313 For a system as complex as the Earth, posing the right questions—ones that will most
314 effectively advance the science—may well be the greatest challenge. One can certainly
315 argue for additional questions, but we have no doubt that our science and the broader
316 society would be well served even if it only focused on the four posed here. Regardless

317 of the questions one poses, meta-scientific challenges must also be addressed to make
318 progress.

319 First, general circulation models constitute one of the pillars of climate science.
320 Shortcomings in their representation of clouds, precipitation and circulation have persisted
321 for many generations of models⁴³, and cause significant problems that remain even when
322 other complexities in the system are stripped away⁵. To gain the most from comprehensive
323 modelling approaches requires energising model development efforts around those
324 processes that most affect the simulation of storm tracks, tropical rain belts and climate
325 sensitivity. Focusing model development efforts around a small set of questions, such as
326 the four articulated above, stands the best chance of reducing long-standing model biases
327 and uncertainties. In the long run, such an approach will also advance the utility of global
328 modelling more broadly, since questions like the future of the permafrost layers, or the
329 dynamics of the terrestrial and ocean carbon sinks depend very much on the magnitude of
330 warming and the distribution of precipitation.

331 Second, the numerous scales and boundless diversity of processes that challenge the
332 modelling also challenge observing systems. Better understanding will highlight gaps or
333 weaknesses in these systems, and therefore will help prioritise the needs for new observations,
334 imaginative field campaigns, or novel reconstructions, synthesis or interpretations
335 of the long-term palaeo-climatic data records. Here again, developing a consensus around
336 the pursuit of a few questions may disproportionately advance the field, for instance by
337 better identifying the needs and opportunities for advancing the palaeo or satellite records.

338 Finally, the convergence of two scientific cultures, one concerned with small-scale
339 convective processes, the other with large-scale climate processes, is the result of an increasing
340 capacity to simulate and observe a range of scales that encompasses both, and
341 thereby study their interaction more fundamentally (see Box 2). By linking water to circulation,
342 this convergence can will lead to important advances in Earth system science.

343 As envisioned by Edward Lorenz forty-five years ago^{44 1}, a deeper understanding of how
344 clouds and moist processes interact with the circulation might help us think about large-
345 scale dynamics as a *dynamics of water systems*, a way of thinking that we believe is a
346 pre-requisite for our science as it endeavours to help a society in urgent need of informa-
347 tion about Earth's changing climate.

348 **Box 1: How do clouds and circulation interact?**

349 The influence of the large-scale atmospheric circulation on clouds has long been recog-
350 nized, and is evident on any satellite picture (Figure 5). In the extratropics, large cloud-
351 systems are caught up in and trace the motions associated with baroclinic and mesoscale
352 waves. In the tropics, clusters of deep clouds trace the ascending branches of the Hadley-
353 Walker circulation, while low clouds cover the ocean in anticyclonic areas. But clouds are
354 not merely sentinels of the circulation, they are increasingly understood to influence and
355 shape the very circulations in which they are embedded. The interaction between clouds
356 and circulation primarily results from three processes: phases changes, radiative transfer,
357 and turbulent transport of air parcels. Condensation and evaporation processes associ-
358 ated with the formation, the maturation or the dissipation of clouds, and the interaction of
359 clouds with solar and infrared radiation, lead to atmospheric heating and cooling perturba-
360 tions, which stimulate waves and turbulence and which affect the horizontal and vertical
361 distributions of temperature on a wide range of scales. In addition, the mesoscale up- and
362 down-draughts that form within cloud systems transport heat, moisture and momentum,
363 and thus rectify the large-scale atmospheric state. Through these various effects, clouds
364 influence both locally and remotely the atmospheric static stability, the wind shear and
365 the meridional gradients of temperature. In doing so they help determine the localization

¹*The previous generation was greatly concerned with the dynamics of pressure systems and talked about highs and lows. Today we have not lost interest in these systems but we tend to look upon them as circulation systems. This change in attitude has led to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems. (Lorenz, 1969)*

366 and strength of large-scale dynamical features such as the tropical Hadley-Walker circu-
367 lation, intra-seasonal oscillations and mid-latitude jets^{25,32,45,46} and influence the rate of
368 development, the structure and the strength of smaller-scale disturbances such as tropical
369 and extra-tropical cyclones, as well as the organization of convection and the occurrence
370 of a range of mesoscale phenomena^{1,41,47,48}. New opportunities now make it possible to
371 improve significantly the understanding of these interactions (Box 2).

372 **Box 2: New Opportunities for Rapid Progress**

373 The clouds-and-circulation problem has been a challenge for a long time, but new oppor-
374 tunities make us confident that a more rapid progress is now possible. Increasing computer
375 power is allowing the representation of motions on the scale of less than a kilometre over
376 domains of thousands of kilometres, even extending to the entire globe (Fig. 6a). Such
377 ultra high-resolution simulations on climate time scales will make it possible to generate
378 clouds and large-scale circulation in a physically consistent manner, and thus to study their
379 interaction. Recent advances in observational capability, particularly satellite measure-
380 ments with active remote sensing, have removed ambiguity in the passive sensing of cloud
381 and atmospheric structure, and enabled a view of how clouds of different depths couple
382 to their large-scale environment (Fig. 6b). Advances in methods of data assimilation—
383 the optimal synthesis of models and observations—are also able to make increasing use
384 of satellite measurements, soon including direct measurements of winds, which provides
385 increasingly consistent and complete pictures of clouds and circulation. Advances in the
386 identification and interpretation of isotopic signatures, available in both the palaeoclimate
387 record and the present day, are giving impetus to investigations of past climate changes
388 (Fig. 6c). Simulations of past and future climates are now being performed using the same
389 models, offering “out-of-sample” tests of our understanding of the role of clouds and cir-
390 culation in climate dynamics⁴⁹. Finally, new methodologies of comparison between simu-
391 lations and observations are now allowing us to not only identify model errors, but to also
392 better interpret their sources⁵⁰.

1. Emanuel, K. The role of water in atmospheric dynamics and climate. In Pearce, R. P. (ed.) *Meteorology at the Millennium*, 1–14 (Academic Press, London, 2002).
2. Sherwood, S. C., Bony, S. & Dufresne, J.-L. Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature* **505**, 37–42 (2014).
3. IPCC 2013. Summary for Policymakers. In Stocker, T. *et al.* (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1–29 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013).
4. Shepherd, T. G. Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience* **7**, 703–708 (2014).
5. Stevens, B. & Bony, S. What are climate models missing? *Science* **340**, 1053–1054 (2013).
6. Bony, S. *et al.* Carbon Dioxide and Climate: Perspectives on a Scientific Assessment. In Hurrell, J. W. & Asrar, G. (eds.) *Monograph on Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, 391–413 (Springer Netherlands, Dordrecht, 2013).
7. Boucher, O. *et al.* Clouds and Aerosols. In Stocker, T. *et al.* (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 571–657 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013).
8. Sherwood, S. C. *et al.* Climate Processes: Clouds, Aerosols and Dynamics. In Hurrell, J. W. & Asrar, G. (eds.) *Climate Science for Serving Society*, 73–103 (Springer Netherlands, Dordrecht, 2013).
9. Held, I. Simplicity amid Complexity. *Science* **343**, 1206–1207 (2014).

10. Held, I. M. & Hou, A. Y. Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Sci.* **37**, 515–533 (1980).
11. Emanuel, K. A. The Dependence of Hurricane Intensity on Climate. *Nature* **326**, 483–485 (1987).
12. Hartmann, D. L. & Larson, K. An important constraint on tropical cloud - climate feedback. *Geophys. Res. Lett.* **29**, 1951 (2002).
13. Cooke, R., Wielicki, B. A., Young, D. F. & Mlynchak, M. G. Value of information for climate observing systems. *Environ Syst Decis* **34**, 98–109 (2013).
14. Stevens, B. & Bony, S. Water in the atmosphere. *Physics Today* **66**, 29 (2013).
15. Rieck, M., Nuijens, L. & Stevens, B. Marine Boundary Layer Cloud Feedbacks in a Constant Relative Humidity Atmosphere. *J. Atmos. Sci* **69**, 2538–2550 (2012).
16. Zhang, M. *et al.* CGILS: Results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models. *J. Adv. Model. Earth Syst.* **5**, 826–842 (2013).
17. Zhao, M. An Investigation of the Connections among Convection, Clouds, and Climate Sensitivity in a Global Climate Model. *J. Clim.* **27**, 1845–1862 (2014).
18. Zelinka, M. D., Klein, S. A. & Hartmann, D. L. Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part I: Cloud Radiative Kernels. *J. Clim.* **25**, 3715–3735 (2012).
19. Butler, A. H., Thompson, D. W. J. & Heikes, R. The Steady-State Atmospheric Circulation Response to Climate Change-like Thermal Forcings in a Simple General Circulation Model. *J. Clim.* **23**, 3474–3496 (2010).
20. Kang, S. M., Polvani, L. M., Fyfe, J. C. & Sigmond, M. Impact of Polar Ozone Depletion on Subtropical Precipitation. *Science* **332**, 951–954 (2011).

21. Brayshaw, D. J., Hoskins, B. & Blackburn, M. The Basic Ingredients of the North Atlantic Storm Track. Part I: Land–Sea Contrast and Orography. *J. Atmos. Sci* **66**, 2539–2558 (2009).
22. Simpson, I. R., Shaw, T. A. & Seager, R. A Diagnosis of the Seasonally and Longitudinally Varying Midlatitude Circulation Response to Global Warming. *J. Atmos. Sci* **71**, 2489–2515 (2014).
23. Woollings, T. Dynamical influences on European climate: an uncertain future. *Phil. Trans. Roy. Soc. A: Mathematical, Physical and Engineering Sciences* **368**, 3733–3756 (2010).
24. Grise, K. M. & Polvani, L. M. Southern Hemisphere Cloud–Dynamics Biases in CMIP5 Models and Their Implications for Climate Projections. *J. Clim.* **27**, 6074–6092 (2014).
25. Ceppi, P., Zelinka, M. D. & Hartmann, D. L. The response of the southern hemispheric eddy-driven jet to future changes in shortwave radiation in cmip5. *Geophys. Res. Lett.* **41**, 3244–3250 (2014).
26. Miyamoto, Y. *et al.* Deep moist atmospheric convection in a subkilometer global simulation. *Geophys. Res. Lett.* **40**, 4922–4926 (2013).
27. Rivière, G., Laîné, A., Lapeyre, G., Salas-Mélia, D. & Kageyama, M. Links between Rossby Wave Breaking and the North Atlantic Oscillation–Arctic Oscillation in Present-Day and Last Glacial Maximum Climate Simulations. *J. Clim.* **23**, 2987–3008 (2010).
28. Bartlein, P. J. *et al.* Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. *Clim. Dynam.* **37**, 775–802 (2011).
29. Marsham, J. H. *et al.* The role of moist convection in the West African monsoon system: Insights from continental-scale convection-permitting simulations. *Geophys. Res. Lett.* **40**, 1843–1849 (2013).

30. Biasutti, M. & Giannini, A. Robust Sahel drying in response to late 20th century forcings. *Geophys. Res. Lett.* **33**, L11706 (2006).
31. Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The Response of the ITCZ to Extratropical Thermal Forcing: Idealized Slab-Ocean Experiments with a GCM. *J. Clim.* **21**, 3521–3532 (2008).
32. Hwang, Y. T. & Frierson, D. Link between the double-Intertropical Convergence Zone problem and cloud biases over the Southern Ocean. *PNAS* **110**, 4935–4940 (2013).
33. Held, I. M., Delworth, T. L., Lu, J., Findell, K. L. & Knutson, T. R. Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Natl Acad. Sci. USA* **102**, 17891–17896 (2005).
34. Perez-Sanz, A., Li, G., González-Sampériz, P. & Harrison, S. P. Evaluation of modern and mid-Holocene seasonal precipitation of the Mediterranean and northern Africa in the CMIP5 simulations. *Clim. Past* **10**, 551–568 (2014).
35. Donohoe, A., Marshall, J., Ferreira, D. & McGee, D. The Relationship between ITCZ Location and Cross-Equatorial Atmospheric Heat Transport: From the Seasonal Cycle to the Last Glacial Maximum. *J. Clim.* **26**, 3597–3618 (2013).
36. Houze Jr, R. A. Cloud clusters and large-scale vertical motions in the tropics. *J. Meteor. Soc. Japan* **60**, 396–408 (1982).
37. Bretherton, C. S., Blossey, P. N. & Khairoutdinov, M. An energy-balance analysis of deep convective self-aggregation above uniform SST. *J. Atmos. Sci* **62**, 4273–4292 (2005).
38. Tobin, I., Bony, S. & Roca, R. Observational Evidence for Relationships between the Degree of Aggregation of Deep Convection, Water Vapor, Surface Fluxes, and Radiation. *J. Clim.* **25**, 6885–6904 (2012).

39. Wing, A. A. & Emanuel, K. A. Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. *J. Adv. Model. Earth Syst.* **6**, 59–74 (2014).
40. Seifert, A. & Heus, T. Large-eddy simulation of organized precipitating trade wind cumulus clouds. *Atmos. Chem. Phys.* **13**, 5631–5645 (2013).
41. Muller, C. J. & Held, I. M. Detailed Investigation of the Self-Aggregation of Convection in Cloud-Resolving Simulations. *J. Atmos. Sci* **69**, 2551–2565 (2012).
42. Neggers, R. A. J., Neelin, J. D. & Stevens, B. Impact Mechanisms of Shallow Cumulus Convection on Tropical Climate Dynamics. *J. Clim.* **20**, 2623–2642 (2007).
43. Jakob, C. Accelerating progress in global atmospheric model development through improved parameterization. *Bull. Am. Meteorol. Soc.* **91**, 869–875 (2010).
44. Lorenz, E. N. The nature of the global circulation of the atmosphere: a present view. *The General Circulation of the Atmosphere* 3–23 (1969).
45. Slingo, A. & Slingo, J. The response of a general circulation model to cloud longwave radiative forcing. I: Introduction and initial experiments. *Q. J. R. Meteorol. Soc.* **114**, 1027–1062 (1988).
46. Bony, S. & Emanuel, K. A. On the role of moist processes in tropical intraseasonal variability: Cloud-radiation and moisture-convection feedbacks. *J. Atmos. Sci* **62(8)**, 2770–2789 (2005).
47. Chagnon, S., Gray, S. L. & Methven, J. Diabatic processes modifying potential vorticity in a North Atlantic cyclone. *Q. J. R. Meteorol. Soc.* **139**, 1270–1282 (2013).
48. Joos, H. & Wernli, H. Influence of microphysical processes on the potential vorticity development in a warm conveyor belt: a case study with the limited area model COSMO. *Q. J. R. Meteorol. Soc.* **138**, 407–418 (2012).

49. Braconnot, P. *et al.* Evaluation of climate models using palaeoclimatic data. *Nature Clim. Change* **2**, 417–424 (2012).
50. Martin, G. M. *et al.* Analysis and Reduction of Systematic Errors through a Seamless Approach to Modeling Weather and Climate. *J. Clim.* **23**, 5933–5957 (2010).

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Figure 1 What role does convection play in cloud feedbacks? Shallow clouds such as those shown on the left (with tops around 2.5 km, and hints of much deeper convection in the distant background) are known to be important in determining the sensitivity of climate system models to perturbations. The behaviour of convection on all scales is thought to be important for determining the response of clouds to a warming climate, particularly for the delicate cloud regimes covering tropical and subtropical oceans.

Figure 2 What controls the position, strength and variability of storm tracks? **a** A mid-latitude winter storm is outlined by the red dashed line (which demarcates the boundary between air-masses in the upper troposphere) overlain on infrared radiances measured with a geostationary satellite. **b** Motion vectors and brightness temperatures are used to deduce the motion and height of the cloud fields from which they are derived. **c** A conceptual cartoon illustrates the interplay between the circulation and a rich variety of cloud fields along a cross section roughly following the transect shown in panel (a). In **a-b** the data is limited by the field of view of the Meteosat satellite (EUMETSAT).

Figure 3 What controls the position, strength and variability of tropical rainbelts? **a** Observations (derived from the satellite Tropical Rainfall Measuring Mission) feature a contrasted distribution of precipitation at the regional scale, with large amounts of rainfall occurring in narrow bands of the tropics. **b** The position of tropical rain bands has a pronounced influence on precipitation over land, with droughts over periods of decades attributable to shifts in the ITCZ, as for instance seen in the Sahel during the 20th Century³³.

Figure 4 What role does convective aggregation play in climate? **a** In models convective organisation emerges spontaneously, increasingly so with increasing temperature⁴¹. **b** In observations (relative humidity profiles from AIRS satellite measurements) the middle troposphere is drier in an atmosphere in which the

same amount of precipitation is concentrated in a smaller number of convective clusters³⁸.

Figure 5 [Box 1 figure] Clouds are closely coupled to the atmospheric circulation but in ways that we are only beginning to discover. (From SATMOS ©Meteo-France)

Figure 6 [Box 2 figure] The power of resolving processes across a range of scales. **a** Simulations of the climate system can now span a range of scales stretching from that of cloud systems (about 1 km) through the planetary scales (shown is the mixing ratio of condensed water simulated with a global cloud-resolving model²⁶). **b** Observations are now capable of profiling the vertical structure of condensate throughout the atmosphere (shown are vertical profiles of radar reflectivity and clouds from CloudSat and Calipso ©NASA and 2007 TerraMetrics). **c** Palaeo records are providing an ever richer and more coherent story of past changes in precipitation (shown is a distribution map of reconstructed lake levels across Africa, 9,000 years ago relative to today ©2012 Nature Education).

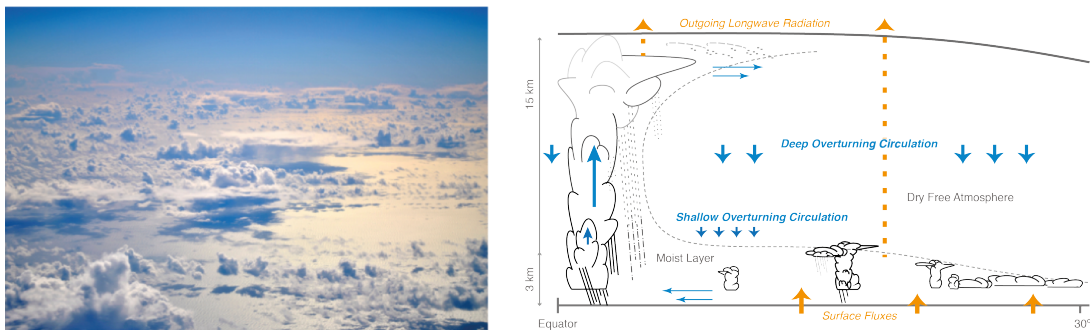


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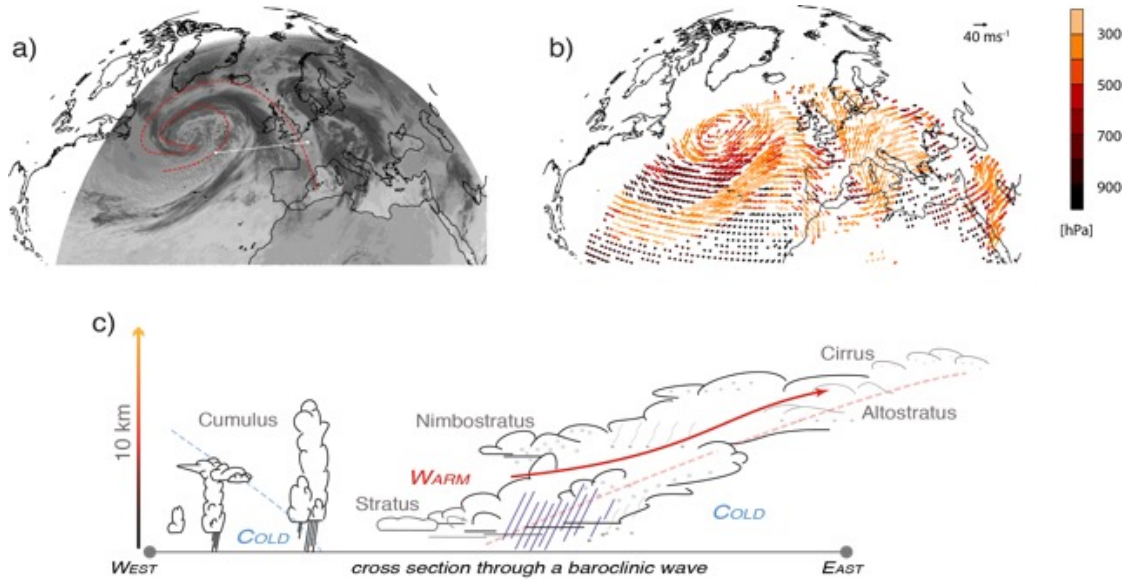


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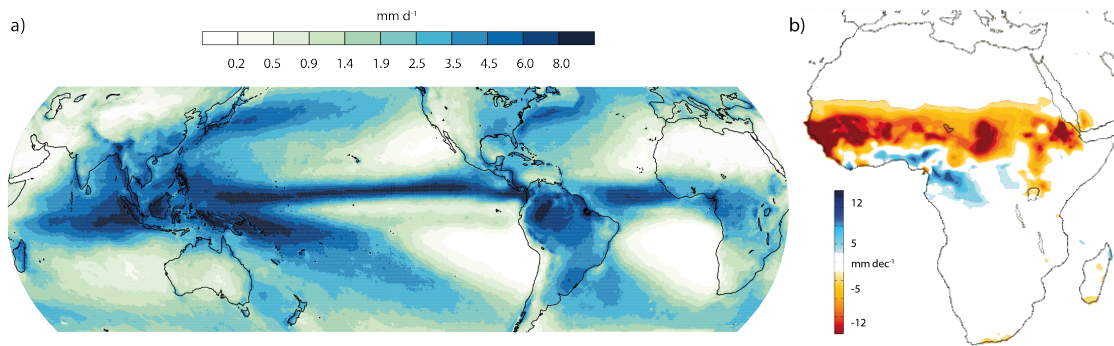


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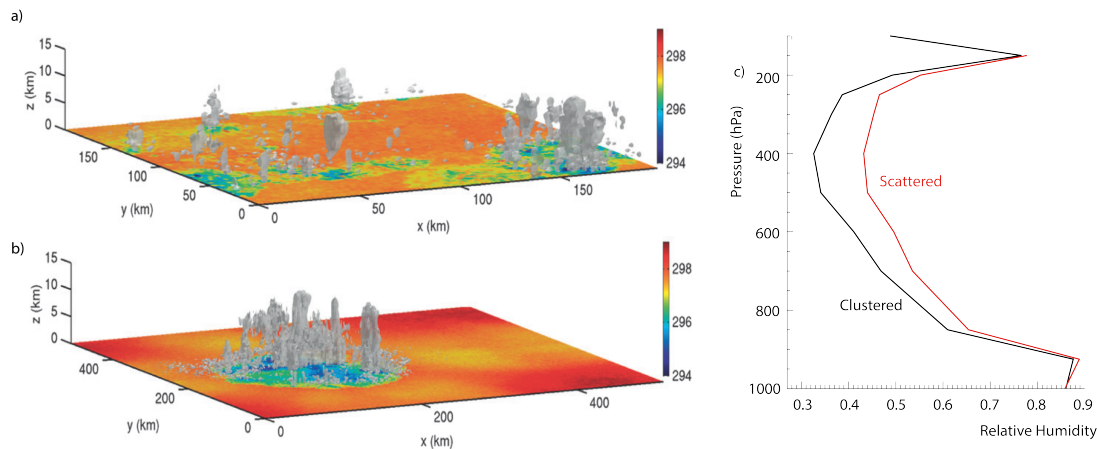


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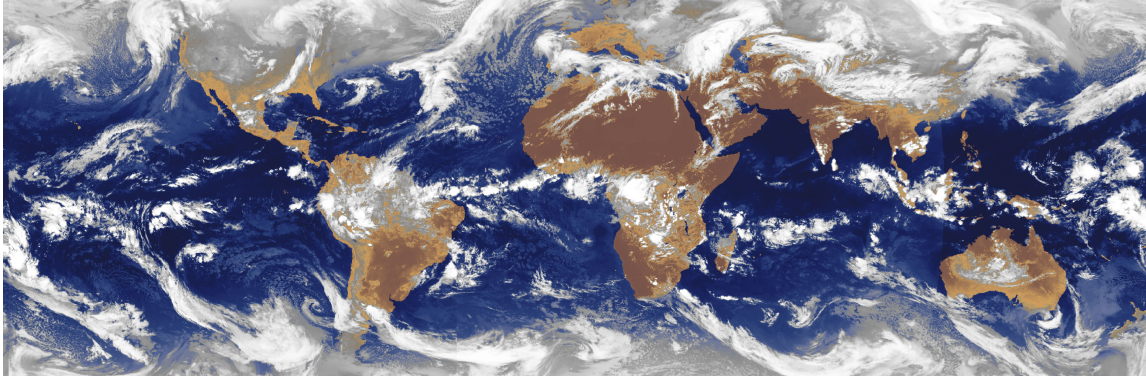


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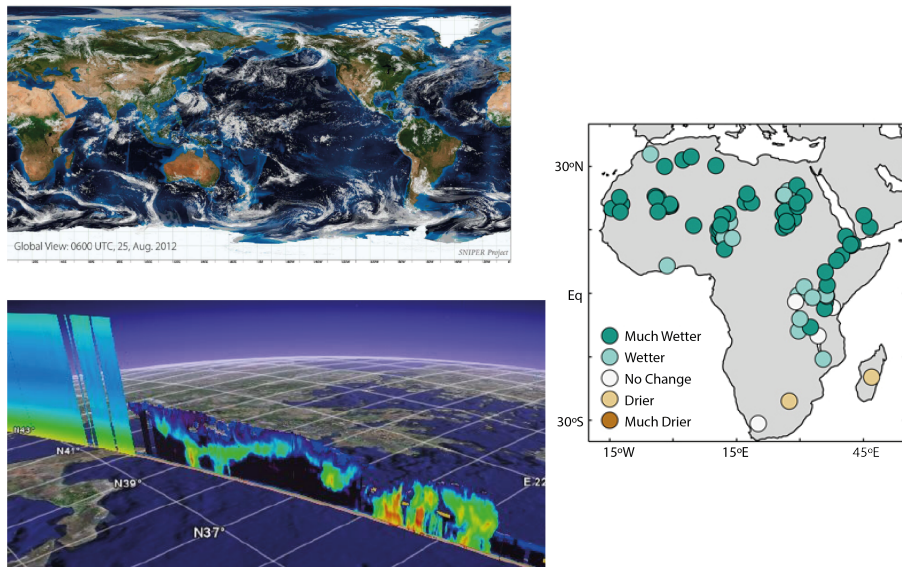


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