If you cannot predict the weather next month, how can you predict climate for the coming decade?

Weather and near-term climate predictions using complex dynamical forecast models are based on the fundamental physical principles of nature: Newton's laws of motion and the laws of thermodynamics. Mathematical models for both weather and climate prediction are thus essentially very similar. However, forecasting the weather or climate are two different aspects of the prediction problem: The weather predictability horizon is limited by the chaotic nature of the atmosphere and its sensitive dependence on the forecast initial conditions. This means that, on average, after two weeks the detailed evolution of the weather becomes unpredictable. Climate prediction does not aim at forecasting individual weather patterns; rather the purpose is to forecast statistics of the climate system averaged over time and space. The predictability of climate relies on (i) the sensitivity of the system to its boundary conditions, such as external radiative forcings in the atmosphere, and (ii) on the long memory of the initial conditions of slowly evolving components of the climate system, such as the ocean. The predictability horizon for climate forecasts is much longer than for weather forecasts.

Suppose you live at a place that is characterised by continental extra-tropical climate conditions with a pronounced annual cycle in surface temperature and rather large variations in its day-to-day weather. The predictability of the daily variations in the weather with its fronts and rain bands or perhaps blocked atmospheric flow patterns remains very limited to a few weeks at the most. Despite the lack of predictability of individual day's weather conditions, there is still obvious scope for predictions on longer climate time scales. Suppose it is early winter. A reasonable climate forecast for that place could be that it is very likely that temperatures in about 6 to 9 months will become warmer, on average, than they are now. Though this example might appear trivial and simplistic because no sophisticated physical forecast model is needed to issue such a forecast, it nevertheless illustrates the point that there do exist sources of predictability that can be relevant on longer time scales even if the weather next month cannot be predicted with high confidence.

In order to better distinguish between the weather and the climate forecasting problem, it is helpful to first define what is meant by "weather" and "climate", and then introduce the concept of two types of predictability: predictability of the first kind and predictability of the second kind. "Weather" means the complete and detailed state of the atmosphere at a particular instant in time. "Climate" is a collective term for the statistics taken from a sample of weather events over a long time. Predictability of the first kind refers to initial value problems where, given some initial conditions, the detailed evolution with time of the state of the system in the forecast model is calculated. Predictability of the second kind relies on the sensitivity of the system to its boundary conditions where the chronological order of states is of no direct concern. Forecasting the weather can effectively be described as the predictability problem of the first kind, while climate forecasting falls mainly into the category of predictability problems of the second kind.

Predictability of the first kind is characterised by the sensitivity of the forecasts to the precise values at the starting time of the forecasts. In such situations small changes in the initial conditions will, on average, lead to widely diverging forecast outcomes. Because the atmosphere is a chaotic system with a high sensitivity to initial conditions, the accuracy of the initial conditions poses a practical limit on the predictability of the detailed evolution of the weather. Even though estimates of the atmospheric quantities used to initialise weather forecast models are derived from real-world satellite and ground-based in-situ observations of the current state, their precise values are not known accurately and thus have an inherent uncertainty associated with them. For weather forecasting, the amplification of these small initial perturbations is the results of the instability of the atmospheric flow and leads to the unpredictability of individual weather patterns after a certain time. The sensitive dependence on initial conditions is sometimes called the "butterfly effect".

The limit after which weather forecasts lose their skill and the weather becomes unpredictable varies and depends on factors like the background atmospheric flow constitution, the specific location and time of year. Detailed weather patterns that identify the atmospheric state at a particular instant in time and space become unpredictable, on average, approximately after two weeks.

Predictability of climate as predictability of the second kind, looks at the ability to predict certain aspect of the statistics of the system over a long time and averaged over an area, rather than predicting the instantaneous local weather conditions. The source of predictability comes from the boundary conditions of the system. Here, the boundary condition sensitivity of the climate statistics exceeds the weather noise from the unpredictability of the first kind. This type of predictability manifests itself as a change in the climate statistics due to a change in an external forcing.

In the climate system, one can think of the boundary conditions as external forcings, for example, the radiative forcings that come from changes to the greenhouse gas concentration in the atmosphere or from changes to the sulphate aerosol load in the atmosphere due to either anthropogenic sources or volcanic eruptions. Or, as another example, the underlying sea surface temperatures can be thought of a boundary forcing to the atmosphere above. As these boundary conditions, or forcings, are not constant in time and vary relatively slowly, knowledge about their future evolution implies a valuable source of predictability for the climate system on longer time scales. Climate variations on large scales resulting from variations in the external forcing are thus partly predictable.

A typical question of climate predictability of the second kind is whether it is possible to predict climate statistics as the results of, for example, increased CO_2 concentration in the atmosphere. Because there is relatively little uncertainty about the near-future evolution of greenhouse gas concentrations, the associated forcings can lead to a noticeable level of predictability for certain climate statistics. For example, there has been a strong warming trend over the last 30 years over Southern European land areas in summer. This warming can be linked to external changes in the radiative forcing and provided a source of decadal predictability if used in retrospective climate predictions of the last decades.

Or think of the short-term climate variations resulting from volcanic eruptions. While the actual eruption of a particular volcano remains very unpredictable on the relevant time scales for climate forecasts, the averaged short-term effects of big volcanic forcing to the radiative balance of the atmosphere are relatively well understood and indicate, once a volcano has erupted, a certain level of predictability for the climate of the coming months and years.

The classification between predictability of the first and the second kind is a useful didactic concept to demonstrate the separate impacts of initial and boundary conditions. In practice, however, many forecasts do not fall exclusively into either of these categories. Rather, the prediction problem becomes a hybrid initial-condition boundary value problem where knowledge of both, the initial conditions of slowly varying component and the boundary conditions are important. This is especially the case in the coupled ocean-atmosphere climate system with its long memory of the ocean initial conditions on forecasts several years ahead. Near-term decadal climate predictions belong to this hybrid prediction type. The question of when exactly the impact on coupled climate forecasts of the initial oceanic state becomes smaller than the impact of an imposed external forcing is an area of active current research.

The sensitivity of the system to an external forcing has been demonstrated for atmospheric circulation regimes of quasi-stationary preferred atmospheric states. These regimes can be very stable to small changes in some external forcing. While the actual structure of the regimes in the atmosphere remains largely unaffected by the imposed forcing, it is the frequency, or probability of occurrence, that is most sensitive to the forcing.

Although the limited predictability of detailed weather patterns implies that the long-term statistics of climate cannot be perfectly predictable in the first sense, it is nevertheless feasible that averaged atmospheric circulation patterns are predictable over extended forecast time ranges beyond the two-week limit of initial condition predictability of atmospheric weather events. Seasonal-mean atmospheric circulation in the extratropics can be predictable on the basis of coupled dynamical climate modes of variability driven by the slowly evolving components of the climate system, such as the ocean and its seas surface temperatures or the land surface with its inherent long memory.

Unlike seasonal-to-interannual prediction systems, decadal prediction systems are very much in their infancy. These systems are designed to exploit both externally-forced and internally-generated sources of predictability. Climate scientists distinguish between decadal predictions and decadal projections, which only exploit the predictive capacity arising from external forcing.

Despite their infancy, decadal prediction systems can exhibit statistically significant skill in predicting near-surface temperature over much of the globe out to at least nine years. A large part of this skill is thought to arise from external forcing like the increases concentrations of greenhouse gases in the atmosphere. Theory indicates that skill in predicting decadal surface temperature should exceed skill in predicting decadal precipitation, and this has proven to be the case. Current research is aimed at improving decadal prediction systems, and understanding the reasons for any apparent skill.

To summarise in general terms, variations in weather and climate can be potentially predictable roughly over a time range comparable with the time scale of the associated variations. Daily weather variations are predictable on the order of several days to a few weeks. Seasonal climate variations may be predictable a season ahead, and longer-term interannual climate variations may accordingly be predictable at longer time ranges. However, while prediction systems are expected to improve over coming decades, the chaotic nature of the climate system will always impose unavoidable limits on predictive skill.

Antje Weisheimer, 2013