Weather/Climate Prediction

Gemalyn Abrajano (Philippines) Md. Ahiduzzaman (Bangladesh) Retcher Ching (Philippines) Krismianto (Indonesia) Zhang Liuhang (Singapore)

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Institute for Mathematical Sciences National University of Singapore

Introduction

This report is based on the project work on "Weather/Climate Prediction" as part of requirement in fulfilling Spring School on Fluid Mechanics and Geophysics of Environmental Hazards (19 April—2 May, 2009). This project work is carried out at the guidance of Dr. Emily Shuckburgh, Natural Environment Research Council (NERC) research fellow based at the British Antarctic Survey (BAS).

This report attempts to give a broad understanding of modern weather/climate prediction systems with a special focus on the model employed by ClimatePrediction.Net and climate prediction results published together with Intergovernmental Panel on Climate Change (IPCC) 4^{th} Assessment Report, which was released in 2007.

This report is divided into five sections, as was the original presentation. The first section provides a brief introduction to the evolution of modern weather prediction systems, which were the precursors to climate prediction systems. The second section focuses on explanation of the specific weather/climate prediction model employed by ClimatePrediction.Net. The third section gives an analysis of future improvements needed to address the current weaknesses of existing climate prediction models. The fourth section draws on the specific case of ClimatePrediction.Net in terms of the objectives and functionalities. The final section demonstrates the climate prediction results published in IPCC report as well as obtained from ClimatePrediction.Net with the implications.

History of Weather Predictions

Numerical weather prediction models

Weather prediction started at the beginning of human civilization. The early weather predictions were primarily based on experience through long-term observations. However, they were especially important in serving the needs of early human agricultural activities, which were highly dependent on the knowledge of changing temperature and precipitation cycles throughout the year. A good example is the 24 "Solar Terms" of the ancient Chinese Lunar Calendar which gives rough estimations of climate conditions throughout the year.

As science and technology developed, with the understanding of Newton's Law of Mechanics and Fluid Dynamics, numerical weather prediction models became available for more accurate results. Lewis Fry Richardson proposed the first numerical weather prediction model in 1920s, and managed to carry out an 8 hour wind and pressure prediction after 6 months of tedious hand calculations. The results turned out to be very inaccurate; however, his effort marked the start of the era for modern numerical weather predictions.

In 1950s, as computer technology advances, numerical weather prediction started to take off. The first successful weather prediction was carried out by Jule Charney and John von Neumann. They used a simplified atmospheric dynamics model to perform a 24 hours weather prediction, which took 24 hours to calculate on the ENIAC computer system. Subsequently, joint US Weather Bureau, Navy and Airforce numerical forecasting unit was formed to provide operational numerical forecast on daily basis.

In the following years till today, numerical weather predictions have achieved breakthrough improvements in many aspects. More accurate and complete atmospheric models are implemented, vertical layers and finer grids are used, more accurate initial conditions are gathered through weather satellites, radars and weather balloons, and much more powerful computer systems are used. Today modern numerical weather prediction models are capable of producing up to 10 days of weather prediction results of relative high accuracy.



Figure 1 Weather prediction accuracy improvement over the years

Climate prediction

"Climate" is generally defined as the average weather. Descriptions of the climate generally encompass statistical information concerning the mean and variability of relevant quantities (e.g. temperature, precipitation, and wind) over a multi-year time period. Climate prediction is achieved based on the advancement of modern numerical weather prediction systems. It attempts to predict limited weather indicators globally in a much longer time frame than typical weather prediction models could produce accurately. There are several important aspects of climate prediction that need to be considered.

- It is impossible to definitively predict weather far in the future due to "chaotic" nature of fluid system
- Climate models must include a description of the evolution of the ocean, interactions with the land and ice, and a representation of the relevant chemistry
- Numerical models have limited temporal and spatial resolution; many processes must be "parameterized"
- Climate model ensembles are used to provide a spectrum of prediction results that incorporate knowledge of the uncertainty
- "Multi-model ensembles" combine multiple predictions of different model systems
- "Perturbed physics ensembles" combine multiple predictions of different parameterization
- ClimatePrediction.Net uses a perturbed physics ensemble
- ClimatePrediction.Net uses HadCM3 (Hadley Centre Coupled Model, Version 3) of the GCM (General Circulation Model) family

Climate Models

One example of a weather prediction /climate model is the UK Hadley Centre's Unified Model. Different versions of this model are used for different puroposes.

Hadley Centre Coupled Model Version 3 (HadCM3)

HadCM3 is a coupled atmosphere-ocean GCM (AOGCM) developed at the Hadley Centre and it was developed from the earlier HadCM2 model and is part of their "Unified Model" family of weather and climate models. HadCM3 is composed of two components: an atmospheric model (HadAM3) and an ocean model, which includes a sea ice model (HadOM3). Various improvements were applied to the 19 level atmosphere model with a horizontal resolution of 2.75° x 3.75° and the 20 level ocean model with a horizontal resolution of 1.25° x 1.25° and as a result the model requires no artificial flux adjustments to prevent excessive climate drift. The atmosphere and ocean exchange information once per day, heat and water fluxes being conserved exactly. Momentum fluxes are interpolated between atmosphere and ocean grids so are not conserved precisely, but this non-conservation is not thought to have a significant effect. The HadCM3 model was used by the Hadley Centre to provide input for the IPCC Third (TAR) and Fourth (AR4) Assessment Reports and used by ClimatePrediction.Net (CPDN) also. A higher resolution version of the Unified Model, HadGEM, was also used to provide results for

AR4. HadCM3 is a very powerful tool: in principle all the different aspects of the simulations can be controlled and studied.

Climate sensitivity



Figure 2 Equilibrium climate sensitivity based on 18 AOGCMs

The standard way to obtain the climate sensitivity is to carry out a computer simulation of the global climate and consider the response to a change in the carbon dioxide level. This provides an estimate of the feedbacks in the climate system. Every AOGCM has climate sensitivity that is defined as the amount of global average surface warming following a doubling of the carbon dioxide (CO₂) concentration. It is likely to be in the range of 2 to 4.5 °C, with a best estimate of about 3 °C (Figure 1). AOGCMs can be used to analyze the effect of different components in the climate system, different AOGCMs give different climate sensitivities.

Current Climate Model Weaknesses and Future Model Improvements

There is a continuous development of climate models to be able to more accurately simulate past and predict future climate changes. Not only the spatial resolution is being taken into account, but factors that have also been observed to affect the climate are now being integrated one by one into the models. This part of the report discusses the weaknesses of existing climate models and how they are being addressed by future model improvements. The focus will be on three aspects – clouds, sea ice, and carbon cycle.

Clouds

A cloud's lifetime may be short but in general, clouds affect the climate because they are important feedback mechanisms for greenhouse effect. Clouds effectively absorb infrared radiation that causes warming of the earth. On the other hand, clouds are also effective at reflecting away incoming solar radiation, which gives clouds a cooling effect on the earth. Any small change in clouds affects the degree to which clouds warm or cools the Earth. Different climate models use different cloud feedback parameterizations, and this accounts for major spread in model-derived estimates of climate sensitivity. Hence, the fidelity of cloud feedbacks in climate models is important for a reliable prediction of future climate change.

There are several steps being undertaken to better represent clouds in the climate models. With the development of better technology, scientists can now have access to three-dimensional global distribution of clouds from satellites. New modelling strategies are being developed, such as using computationally-intensive climate models that resolve some of the smaller scales of motion influencing the cloud's cover and radiative properties. Cloud-resolving models (CRMs) are also being developed, with spatial resolutions of less than a few kilometres as opposed to 100 square kilometre span of a grid box of current models. This will provide better results by explicitly representing many cloud properties in the simulations. The high-resolution CRMs are embedded in each grid-box of a traditional GCM, as seen in the figure below. CRMs eliminate the need for extensive parameterizations but are very expensive to run.



Figure 3 Higher-resolution CRMs that better represent clouds are embedded into traditional GCMs for a more reliable cloud feedback computation

Sea Ice (Arctic in the 21st Century)

Sea ice, like clouds, is an important feedback mechanism for climate change. This is due mainly to the sea ice's high albedo, meaning it reflects a lot of light. In contrast to the darker sea water beneath it, sea ice absorbs less solar energy, which keeps the Arctic cool. The cold temperature in the poles act like an air-conditioner to the Earth, and the contrasting temperatures between the poles and the equator set-up circulation in the atmosphere and oceans that lead to weather patterns around the globe. In the IPCC Models A1B Scenario, out of the 16 climate models, more than 50% predicts an almost ice-free Arctic by the end of this century. The CCSM3 (Community Climate System Model Version 3), whose values are very close to the observed values, predict a very abrupt reduction in the first half of the century. This dramatic decline of the volume of sea ice is an important aspect of climate change; therefore it is important to represent it well in climate models.

To be able to better study sea ice, several aspects are being looked into. One is looking at the thickness of the remaining sea ice, as opposed to looking at just the extent. Scientists are interested to know if the sea ice is thinning, because thin sea ice will melt more quickly than thick sea ice. Satellite sensors use the difference in elevation and reflectance between surfaces to be able to measure the thickness. In terms of reflectance, ice is highly reflective, snow is less reflective, and water is the least reflective.

Carbon Cycle

The carbon cycle and the physical climate system affect each other greatly. Any change in the climate affects the exchange of atmospheric carbon dioxide between the land surface and the ocean, while changes in the carbon dioxide fluxes affect the Earth's radiative forcing and so affects the climate system. Recent AOGCMs now include the carbon cycle and the results confirmed the potential for strong feedback between it and the global climate. AOGCMs with coupled carbon cycle are able to predict atmospheric carbon dioxide concentrations using anthropogenic emissions rather than assumed concentrations.

Carbon dioxide has a positive effect on vegetation, as seen in an experiment where better vegetation growth was observed when there is a higher concentration of carbon dioxide. More vegetation will absorb more carbon doixide and provide a negative feedback. However, studies have shown that the increase in the amount of carbon dioxide that the Earth has now has led to a doubling of the likelihood of a heat wave similar to that in Europe in summer 2003. Such heatwaves can adversely affect vegatation., leading to a positive feedback. These positive and negative feedbacks highlight the importance of coupling the carbon cycle in climate models for a more reliable climate change predictions.

ClimatePrediction.Net

Climateprediction.net is a distributed computing project to produce predictions of the Earth's climate up to 2080 and to test the accuracy of climate models. The aim of climateprediction.net is to investigate the approximations that have to be made in state-of-the-art climate models. By running the model thousands of times (a 'large ensemble') to find out how the model responds to slight fine tuning of these approximations. In this way Climateprediction.net is able to better represent the range of uncertainty of future climate predictions.

How the model works?

The model used by climateprediction.net is the UK Met Office's Unified Model version HadCM3, which is described above. It is designed to be downloaded and run on a standard PC. Once when you install the software on your computer it gets instruction from server automatically and the required applications and input files of the experiment will be downloaded automatically on your and compute. The climate prediction model needs a long time for a complete run of an experiment, typically 2-4 weeks. When model run is completed, the software then uploads the output file and reports the results. Then you can get a summary of results for analysis.



Figure 4 Shows the interaction between user computer and the server of climateprediction.ner (http://climateprediction.net/content/modelling-climate accessed on 27.04.2009)

How to get the results from the model

To link up the user computer with the server, it is needed to install BOINC Manager. It is can be downloaded form http://boinc.berkeley.edu/. After completion of a complete run of the model it is needed a visualization package to view the results. This package can be downloaded form www.climateprediction.net/schools/cpdn_viz2.exe



Figure 5 Example of the cylindrical equidistant projection used by climateprediction.net graphics for temperature gradient (http://climateprediction.net/content/modelling-climate accessed on 27.04.2009)

Experimentation and Validation of the model

Validation of the model involves comparing the statistics of the model output with the statistics of the observed atmosphere. The experimental set-up is what is know as a time slice experiment running the simulations from 1959- 2000. This period is broken up into 2 year periods, which overlap, e.g. there is a period from 1961-1963 and a period from 1962-1964. This allows examining how the model diverts from its initial starting conditions and removes any bias that may be caused by the model "spinning up" into a stable state.

IPCC and climateprediction.net Results

One of the important figures that is found in IPCC is the graph which involves temperature increase (°Celsius) with respect to time. Figure 1 below shows the two different sets of situations (a) temperature increase that involves both man-made (anthropogenic) and natural forces that

involve climate change. Such examples of anthropogenic forces are fossil fuels, CFCs, etc. (b) temperature increase that only involves natural forces. Notice in (a) how the red line shows a similar curve to the observed line (black line). As compared to (b) where our temperature will not increase without if we did not emit any anthropogenic forces. We can therefore say that it is likely us humans who are causing an increase in global temperature.



Figure 6 Diagram of Temperature vs Time for (a) anthropogenic and natural forces and (b) natural forces only

Sea level rise is also one main concerns and it can be seen in the figure below that by the end of the century, sea level is predicted to increase by an amount of 50 cm if assuming that CO2 emissions are doubled (however, these estimates are very uncertain due to uncertainty in the future evolution of ice sheets).



Figure 7 Sea Level Height vs Time. Gray part shows the uncertainty and unknown sea level, Red part is the reconstruction of global mean sea levels based from tide gauges. Green line is sea level rise based from satellite altimetry. Purple part is the projections of sea level based from the gray and red part.

In parallel with the CO2 increase, if the sea level increases then it is most probable that the ocean's pH will also decrease from a current pH of 8.1 to approximately 7.8. Obviously, our marine life will be entirely different when that happens.



Figure 8 CO2 increase is inversely proportional to the ocean's pH. Certain marine life will be threatened or even become extinct when our ocean's pH level will become more and more acidic

For the very long term effects of the rise of CO2 emissions (anthropogenic forces), just as before, the observed values of temperature increase are located in the beginning of the graph up to present (black line). Now, lets take a look at the A2 situation – assuming a 1% increase in our CO2 emissions per year we can see an approximately exponential increase in our global temperature (which is represented by the red line) and to think that we are currently emitting more than 1% of CO2 already. For the 2nd case, A1B, this is assuming that we have a balanced economic growth, and we can see that there will still be a big increase (green line) but not as bad as the A2 situation. Furthermore, for the 3rd case, B1, this is assuming that when the world is united and is working as one (blue line) and we can see that our global temperature will decrease by half with respect to the A1B situation. Lastly, assuming if we stop CO2 emissions, there will be a minimal increase in our temperature (orange line) although this situation is highly unrealistic.



Figure 9 Temperature vs Time based on different CO2 emission scenarios

In conclusion, although climate prediction may not be as accurate especially when it comes to the long term, it is proper to assume that all these different emission scenarios have a common approximate of temperature increase value in the next few decades. This is where climate modeling and prediction can help us forecast the upcoming climate conditions that we will need to face and adapt in the future.