Introduction: Exascale computation in NOAA for predicting weather and simulating climate change.

The fastest supercomputers reached 1 petascale (10^{15} floating point operations/sec or flops) in 2012. Exascale computers are a thousand times faster (10^{18} flops) and are expected to become available in the next decade. We briefly discuss why access to such an increased computer power with time has been and continues to be essential at NOAA both for improved weather prediction and for realistic simulation of climate change.

Currently (2016) the two supercomputers used for numerical weather prediction (NWP) at NOAA have a speed of 2.89 petaflops each. Why would NOAA need to increase their power, again, by ~1000 times?

NWP is computationally very costly: From the beginning of NWP science (in the 1950's), Weather Services have used some of the fastest supercomputers available. Why? Because one of the most important factors that determine the accuracy of the forecasts is the model resolution. At the beginning of NWP, atmospheric models had a single vertical layer (they were quasigeostrophic barotropic models) and a horizontal resolution (grid size) of the order of 500Km. When primitive equations models replaced the barotropic model, they required about 2-3 orders of magnitude more computations. For example, the successful and widely used Limited Fine Mesh (LFM) model implemented in 1971 had 200Km horizontal resolution and 7 vertical levels). This resolution is still coarse to resolve well even long atmospheric waves, and therefore its weather forecasts became useless after about 3 days. Doubling the resolution of a model in each of the horizontal directions increases the number of horizontal grid points by 4, and, since the time step also needs to be halved, it requires the computer power to increase by a factor of 2^3=8. If the vertical resolution is also doubled, the computer power needed to run a model with double resolution increases by a factor of 16!

The global model implemented at NCEP in January 2015, with a horizontal resolution of 13Km and 64 vertical levels thus required about ~$7.5\text{x}10^4$ more computer power than the less than hemispheric LFM did. In addition, the introduction of ensemble forecasts in 1992, increases the model cost by about 20 (allowing for the use of lower resolution in the ensembles). The use of advanced data assimilation systems, essential to initialize the model forecasts, doubles again the computational cost of the 2015 global model compared with the LFM to about $2\text{-}3\text{x}10^6$.

This agrees quite well with Moore's law (computer power doubles every ~2 years, or it increases by ~1000 in about 20 years). The Wikipedia figure below shows that from 1971 to 2012 the increase of CPU transistor counts against the date of their introduction is fitted very well by exponential growth doubling every two years, which increased by a factor of 10^6 during this period. This shows that the NWS for the last 45 years has been increasing the resolution of the models at close to the maximum allowable speed by Moore's law. If the exascale supercomputers become available in the early 2020's, this increase of 1000 in computer power in about 10 years would be faster than the historic 20 years for such an increase in speed.

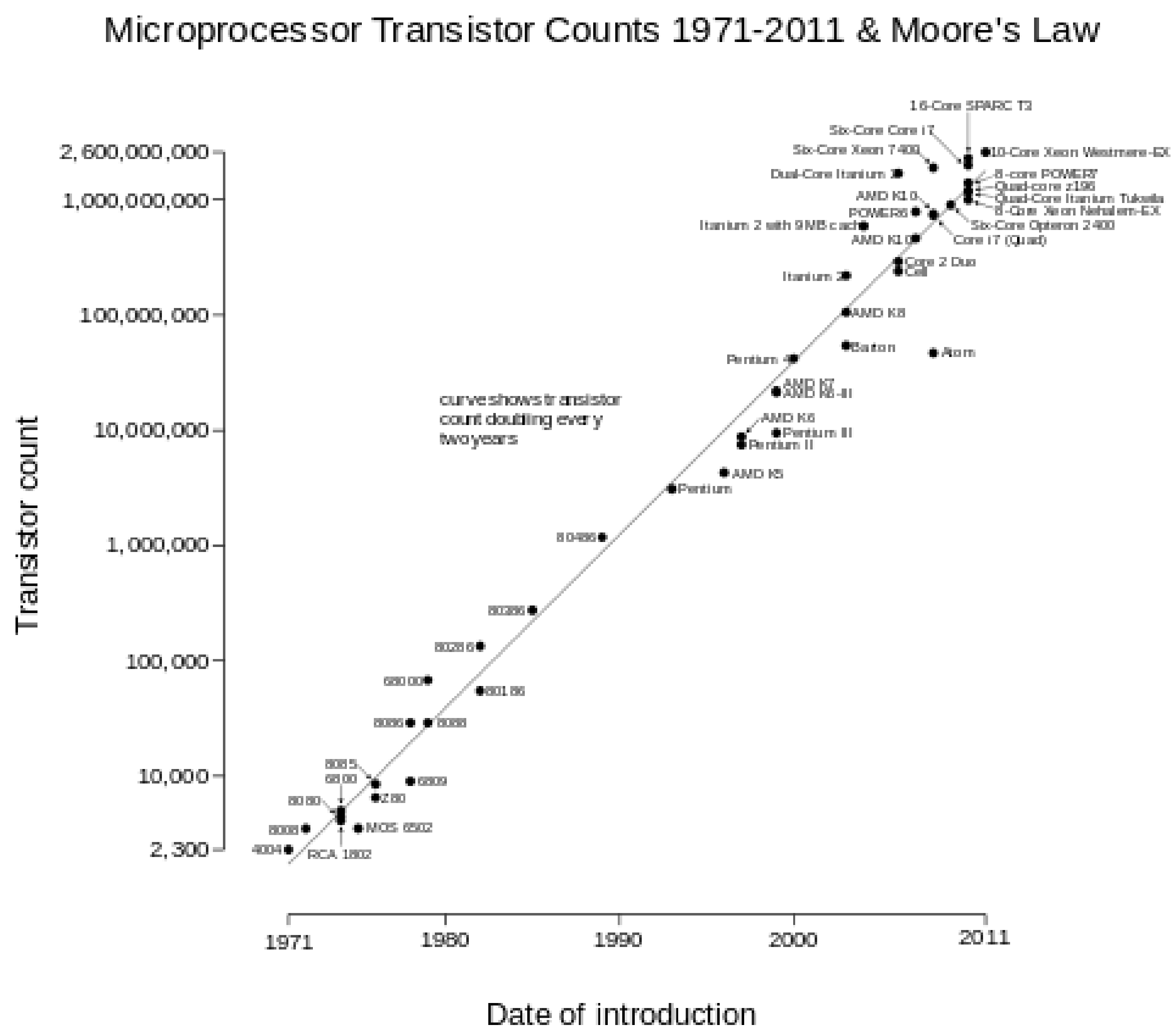

Figure 1: Plot of CPU transistor counts against the dates of their introduction. The line corresponds to exponential growth with transistor count doubling every two years. (From Wikipedia, July 2016, Moore's law).

Of course, in addition to just the "brute force" approach of increasing the model resolution, the model forecasts were and continue to be substantially improved by other major scientific improvements that take place at the same time as the increase in resolution: 1) The quantity and quality of the observations, 2) The model physical parameterizations of subgrid scale processes, and 3) The methods for data assimilation that create more accurate initial conditions. These three basic components of NWP, observations, models, and data assimilation (that creates the initial conditions or analysis), are closely coupled in NWP and need to be improved at a similar rate, as shown in schematic Figure 2. ("If one of the components of the NWP chain is not improved, the chain will break at its weakest link", J. Smagorinsky lecture on NWP, ~1980). In conclusion, in order to continue the amazing historic advancement of NWP and provide more accurate, useful forecasts both in longer time scales (seasonal to interannual, using coupled ocean-atmosphere models), and shorter (e.g., severe storms, tornados, using nested regional high resolution models) time scales, scientific advances in NWP have to continue to take place with access to the fastest supercomputers.

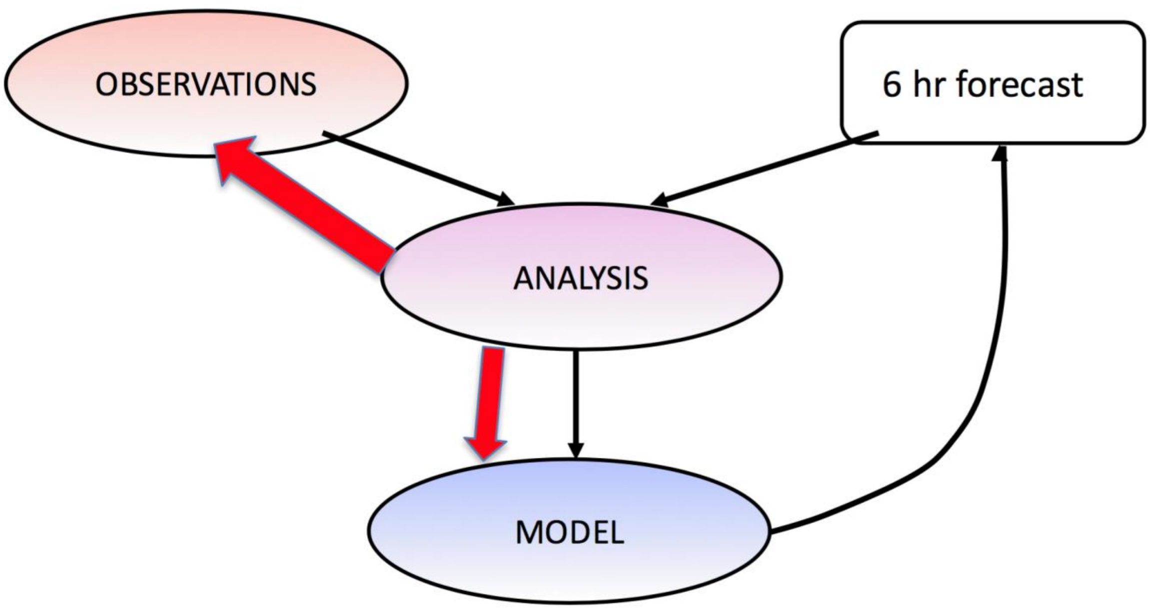

Fig. 2: Schematic of the 6-hour Analysis Cycle: The Analysis combines optimally the model 6hr forecast and the new observations, and creates the initial conditions for the next cycle. This approach (black arrows) is known as Data Assimilation. In recent years scientists have started exploring methods to use Data Assimilation to improve both the observations and the model (red arrows). Kalnay (2018).

NOAA's responsibility does not end with the production of better weather forecasts to protect welfare, life and property. Equally or more important, it has to inform and guide the policies addressing climate change by estimating realistically the impact of anthropogenic forcings on climate. In a stimulating and interesting paper Palmer (2016) proposed that the power of exascale supercomputers (and the human power of many physicists who should change their scientific careers to meteorology, like Palmer did) should be devoted to improving the climate models, which currently have a horizontal resolution about 10 – 50 times lower than weather models. He pointed out that a prediction of convective rain looks quite realistic in a 1Km resolution regional model forecast, whereas climate models' simulations of precipitation are very easily identified as "not being real". An advantage that climate models have is that their output is climate and climate change, so that the accuracy of individual "forecasts" is irrelevant as long as the statistical properties of the climate model integrations are realistic. This implies that stochastic parameterizations can lead to more realistic model simulations, and as a result, the model computations can be computed at a lower precision than currently used.

Palmer (2016) strongly suggests that "Climate science must now step up a gear to provide reliable estimates of the climate of the coming decades, including climate extremes, on both global and regional scales, which are as sharp as possible." In order to do this, he calls (in Europe) "for a new European Programme on Extreme Computing and Climate to advance our ability to simulate climate extremes, and understand the drivers of such extremes. A key goal for such a programme is the development of a 1 km global climate system model to run on the first exascale supercomputers in the early 2020s."

References

Kalnay E. 2018: Atmospheric Modeling, Data Assimilation and Predictability (Cambridge University Press, Second Edition).

Palmer TN. 2016 A personal perspective on modelling the climate system. *Proc. R. Soc. A* **472**: 20150772. http://dx.doi.org/10.1098/rspa.2015.0772.