Numerical modeling, from weather to climate: Progress achieved, and some of the reasons promising further progress

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One hundred years of Milanković's theory of climate change

Belgrade, November 18, 2020

Milutin Milanković (1979-1958), in 1913, having accepted a professorship in applied mathematics in Belgrade, was looking for a field in which he could use his mathematical talents …

Milanković, 1930

… a schematic … three concentric circles. Mathematics … symbol of a Sun, in the center. … Shining upon all of the exact sciences inside the nearest circular region … But barely entering the descriptive natural sciences of the one beyond. … I decided to have a look into these borderline sciences and started with Meteorology. …

Asked Vujević, any papers . . . with considerable use of mathematics? He gave me several of those."

One: distribution of solar energy on the Earth's surface

The initial equation: erroneous!

Weather prediction?

"I was struck looking at the difficulty of the task.
The variety of Earth climates bewildered me, clouds of the sky would make be frown, every rain would make me depressed, and when a gust of wind would come by, in particular the Belgrade's koshava, I would ask myself "Who could capture all the whims of Aeolus into mathematical formulas ?"

"... all that evolves in such a complicated manner that, at least for the time being, it seems impossible to subject these phenomena to a mathematical analysis to a degree which would enable one to foresee their succession".

However, Milanković found comfort in the idea that

"... every region on Earth ... has its average climate which ... has not changed much over the centuries. This ... can be the subject of mathematical analysis."

Eventually, the time did come . . .

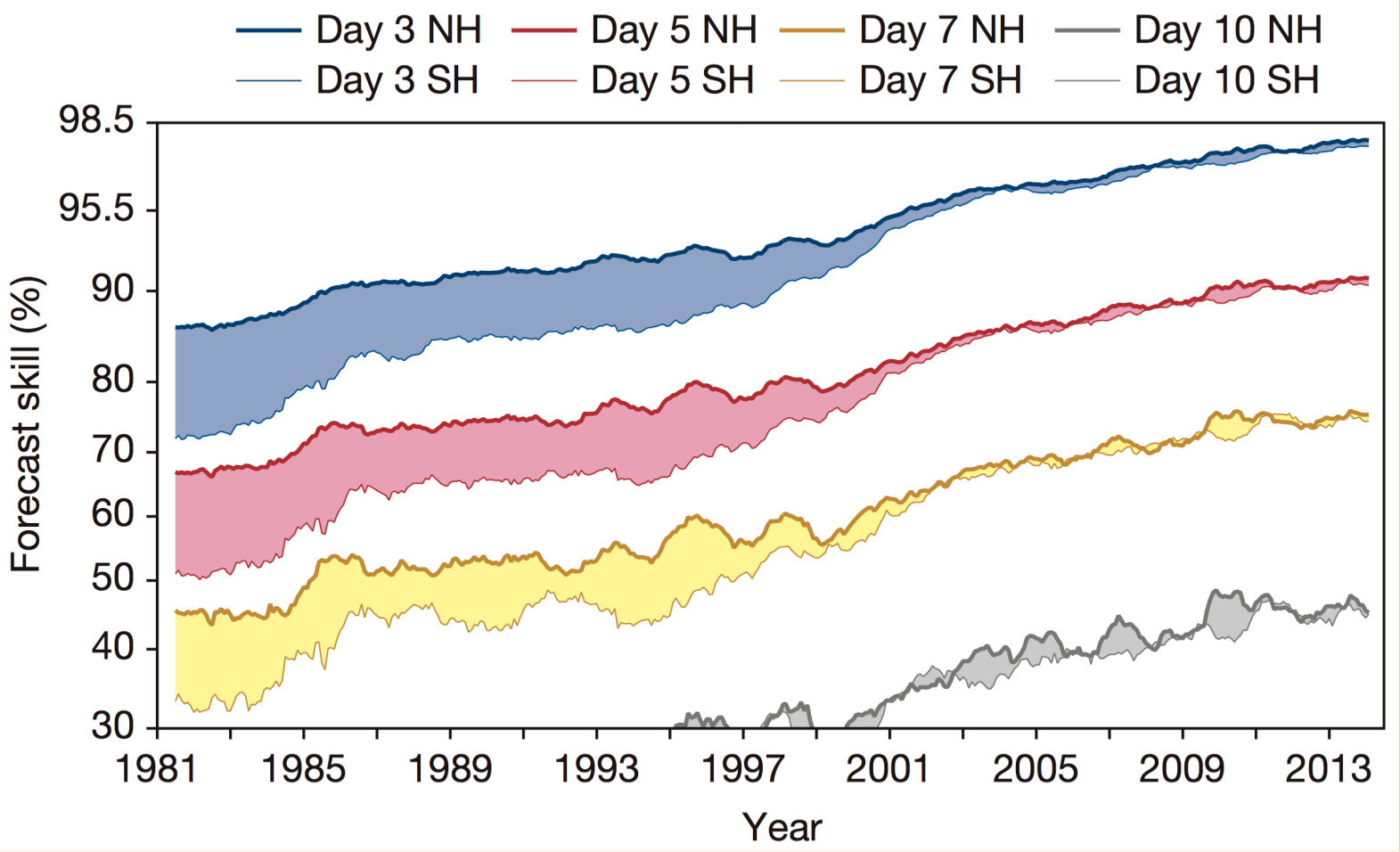
Numerous necessary steps . . .

An illustrations how far this took us:

Weather: one illustration of progress in both the data assimilation and the predictive skill of models:

Near disappearance of skill difference between extratropical data rich northern and data poor southern hemisphere

500 hPa height anomaly correlation, forecast (ECMWF) vs. observed:

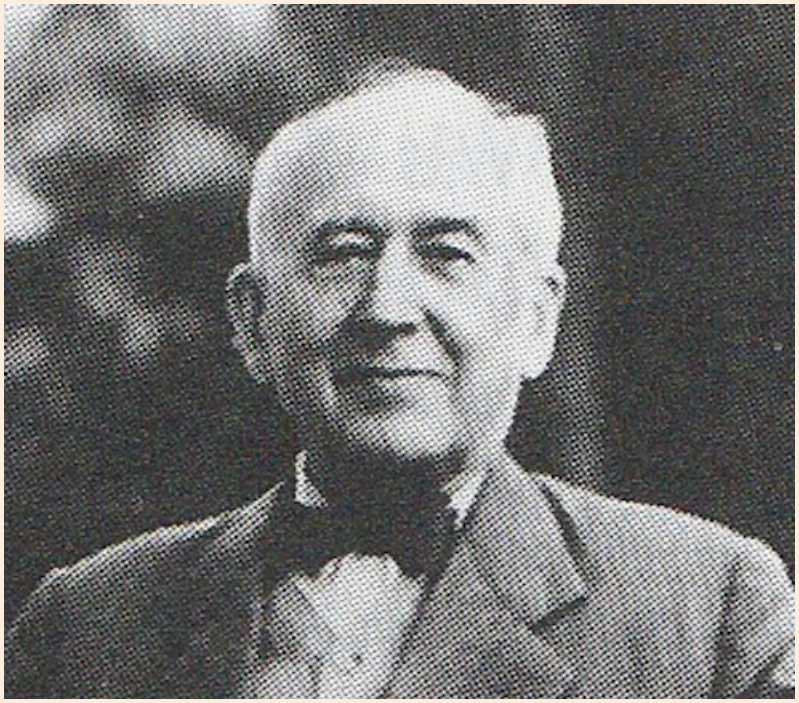


From:

Bauer et al., The quiet revolution of numerical weather prediction. Nature, 2015

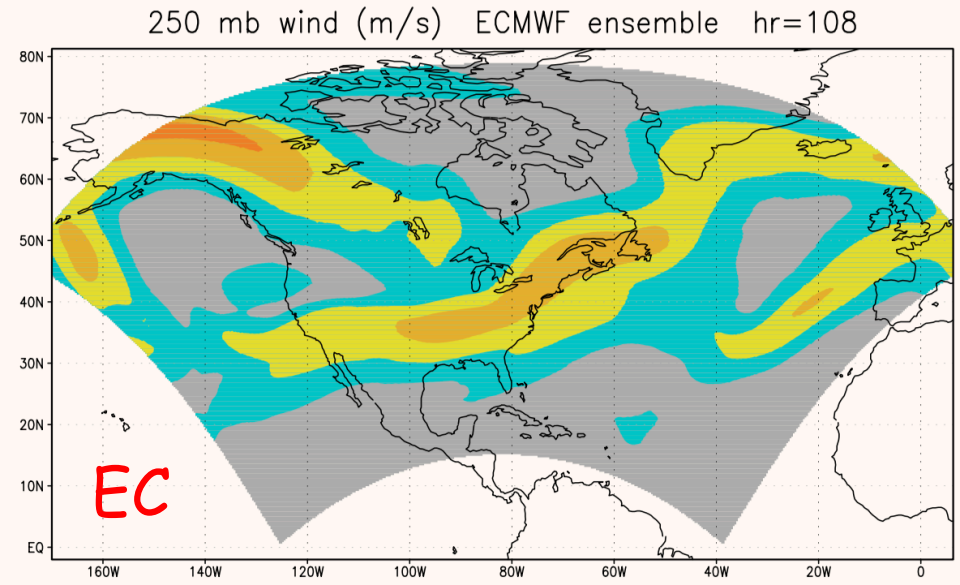
Skill achieved by a model largely from Milanković's part of the world:

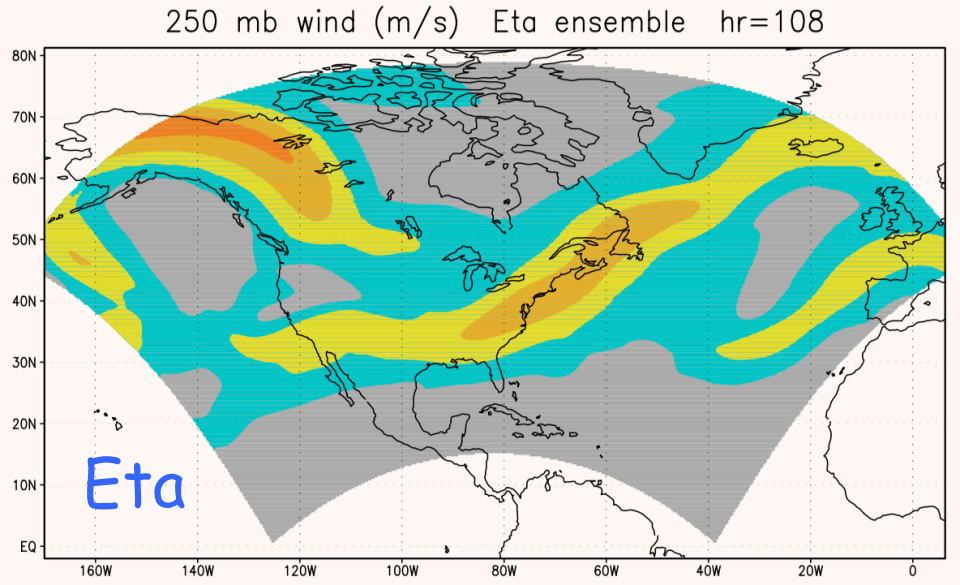
Mesinger, F., and K. Veljovic, 2020: Topography in weather and climate models: Lessons from cut-cell Eta vs. European Centre for Medium-Range Weather Forecasts experiments. J. Meteor. Soc. Japan, 98, https://doi.org/10.2151/jmsj.2020-050



MM, 1952 (From: Milutin Milanković 1879-1958, EGS, 1995)

Plain Language Summary: Advantages and issues of methods of incorporating topography . . . Terrain-following coordinates used in almost all major models do have issues with steepness of model terrain exceeding a given limit. Immersed boundary methods . . . Cut-cell schemes prescribe bottoms of their lowest cells to define topography and are able to use finite-volume discretizations. New views are offered via analyses of experiments driving cut-cell Eta by European Centre for Medium-Range Weather Forecasts (EC) 32-day ensemble members.





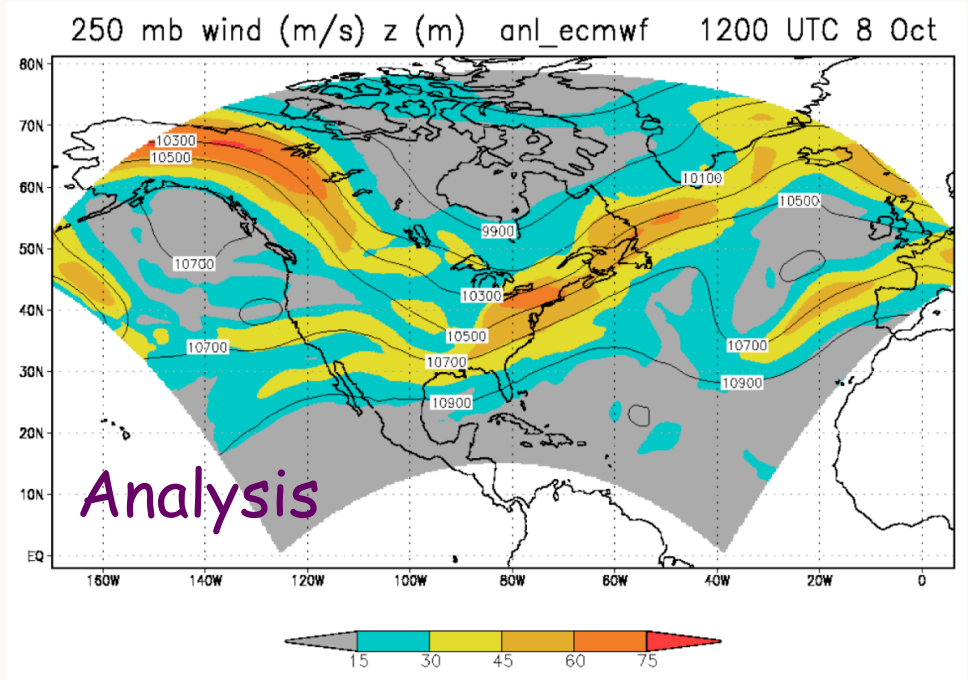
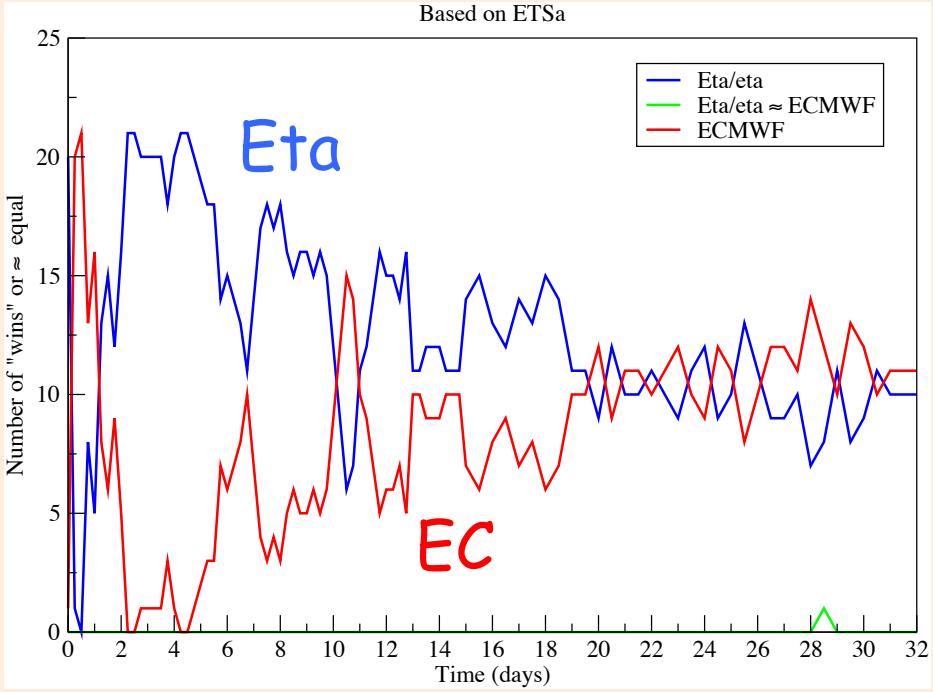


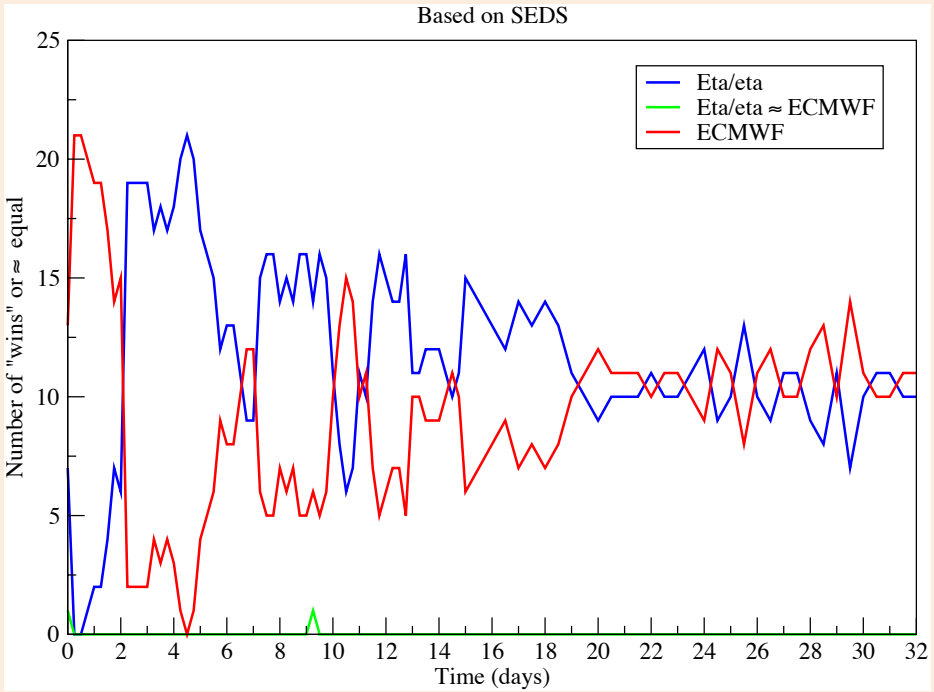
Figure 1. Above: 21 member ensemble averages of 250 hPa wind speed at 4.5 day time. EC driver members left, cut-cell Eta members right. Verification analysis below. Note the more accurate Eta southeastern extension of the > 45 m/s jet streak along the eastern slopes of the Canadian Rockies, and the improved position of these speeds off New England States and across eastern Labrador toward the southern tip of Greenland. All 21 Eta members at that time had better SEDS and ETS (or Gilbert) scores adjusted to unit bias (ETSa) than their EC driver members. Initial time 0000 UTC 4 October 2012.

How many of the 21 Eta members placed "jet stream winds" better than their driver EC members ?

"jet stream winds" : wind speeds at 250 hPa > 45 m/s

Two skill scores used: ETSa, SEDS (higher is better)





ETSa: Equitable threat score adjusted to unit bias

SEDS: Symmetric extreme dependency score

What does this Eta advantage come from ?

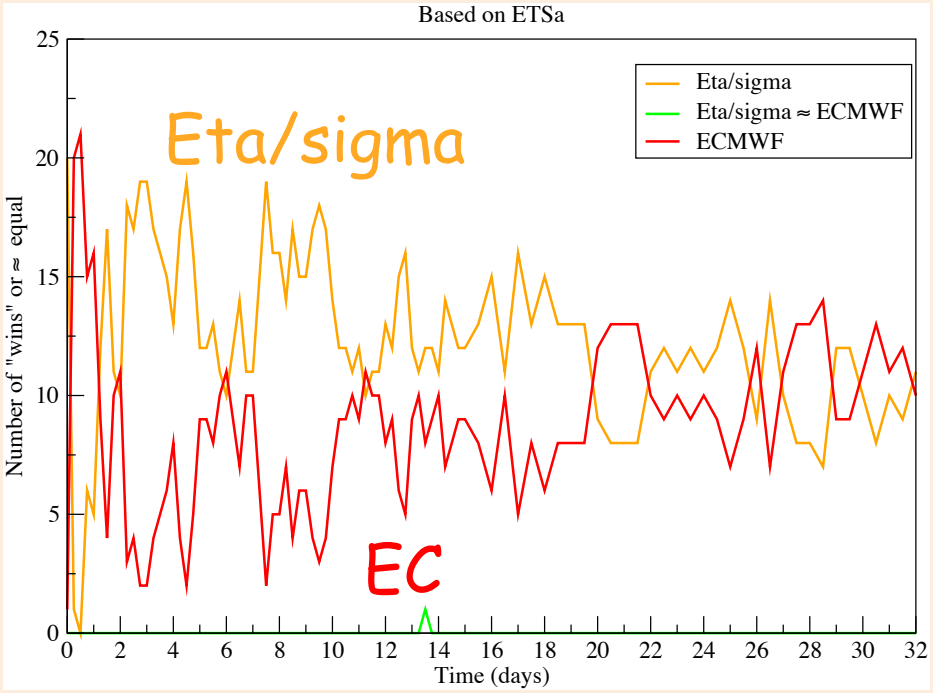
Information we have:

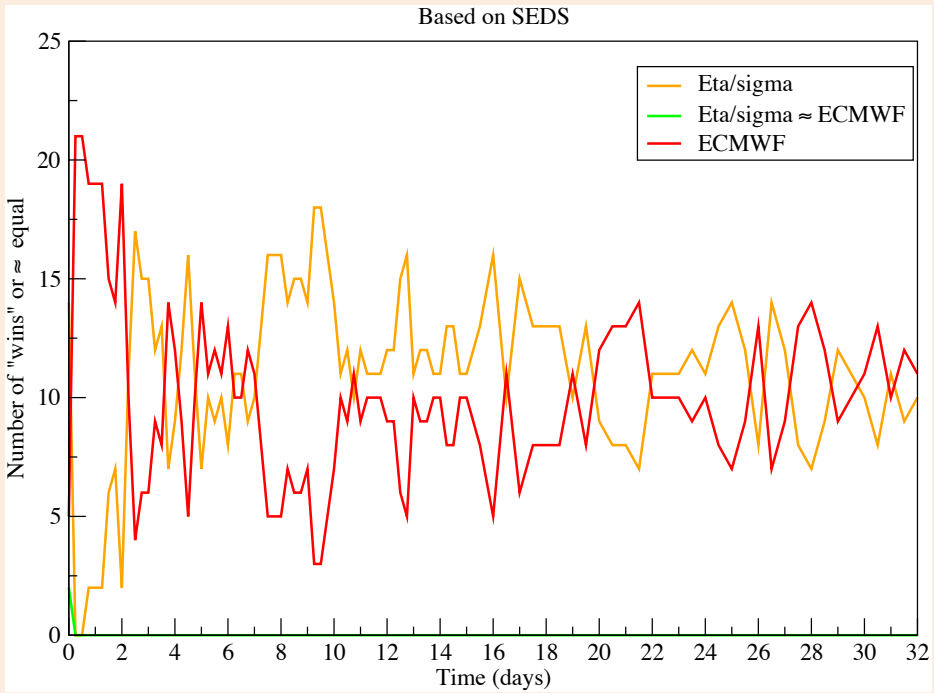
Impact of the choice of the vertical (eta) coordinate,

intersecting as opposed to following topography

In Eta, one can switch the vertical coordinate to follow topography,

"sigma" → Eta/sigma





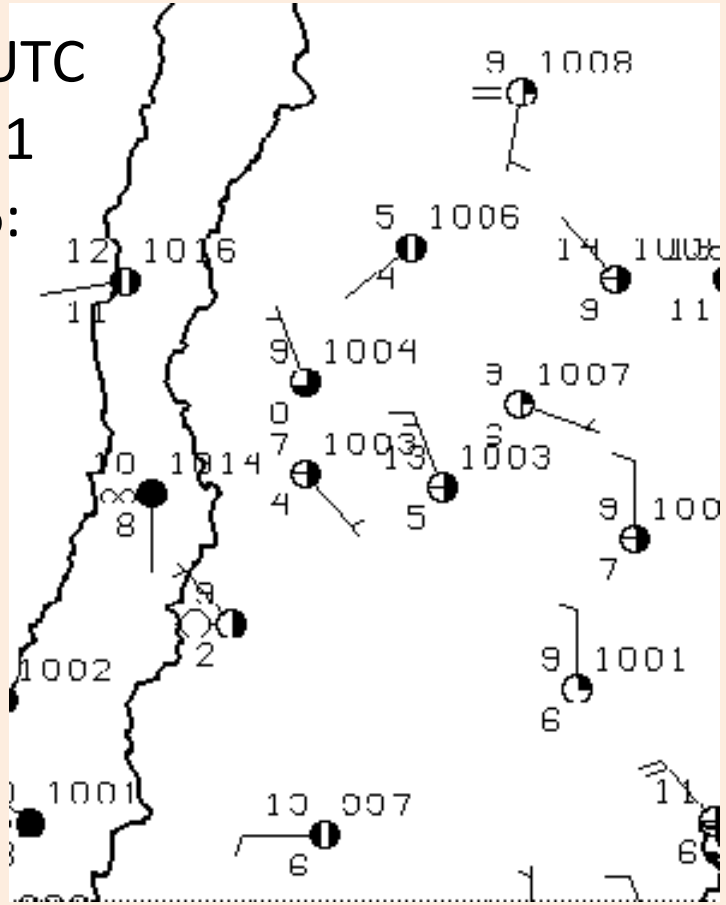
The Eta still "wins" but not that convincingly . . .

So Eta must have other features that contribute to its advantage over the EC

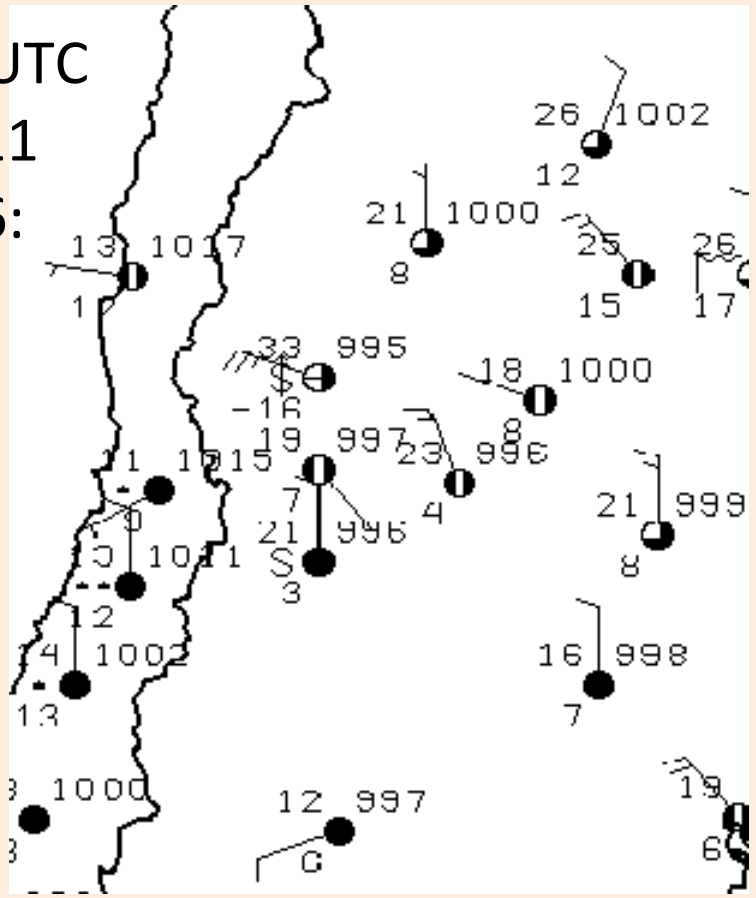
Finite-volume vertical advection ?

“Zonda” wind, synop observations:

1200 UTC
July 11
2006:



1800 UTC
July 11
2006:



Note the station San Juan

with 2 m T°C increase from 9 to 33°C in 6 hrs !

Experiments at NCEP:

Experiment 1: Step-topography Eta, 8 km/60 lyr, GFS fcst LBCs

Experiment 2: same, but cut-cell Eta (2007 code);

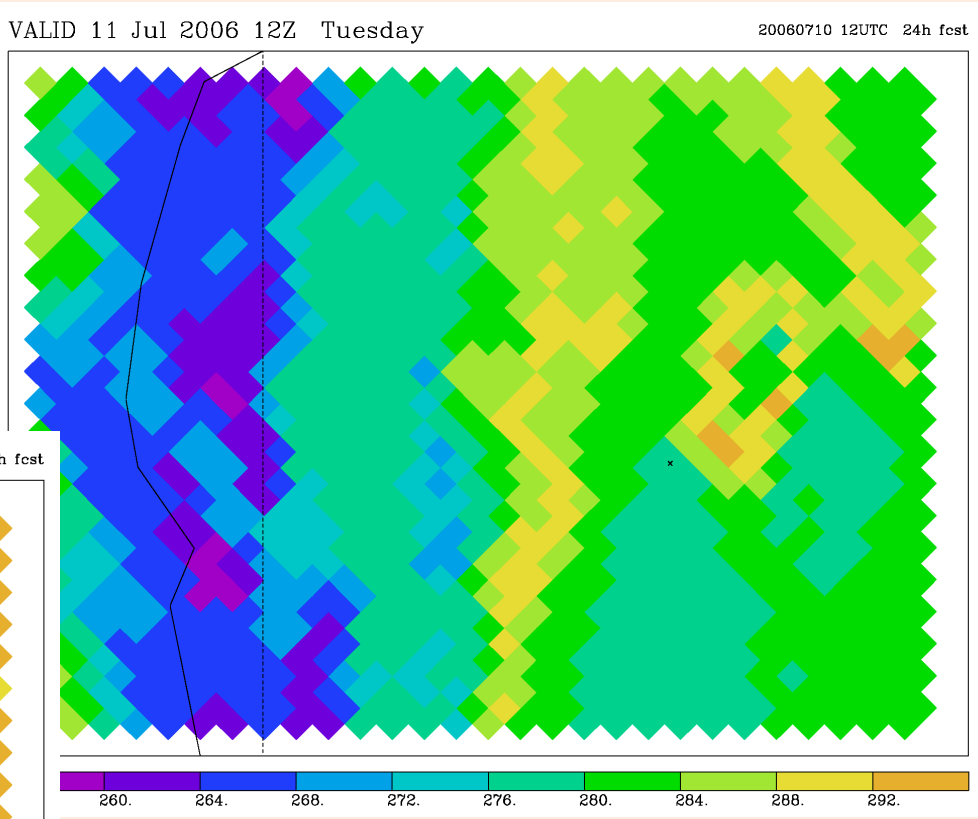
Experiment 3: same, but the Eta vertical advection scheme changed from the centered "Lorenz-Arakawa" to the van Leer type piecewise linear scheme of Mesinger and Jovic (2002, NCEP Office Note 439)

Motivation: This makes the Eta very nearly a finite-volume model, and avoids a problem of the centered scheme of false vertical advection from below the ground !

Step topography Eta

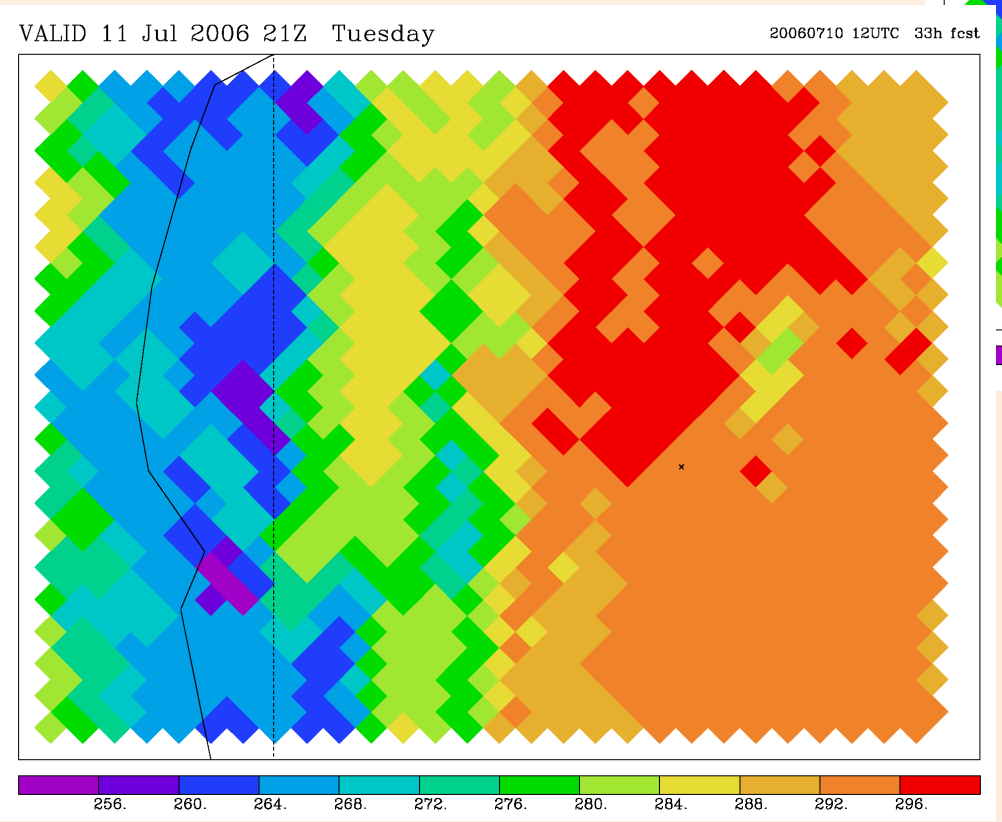
NCEP 2006 operational version

Lowest layer T



24 h fcst

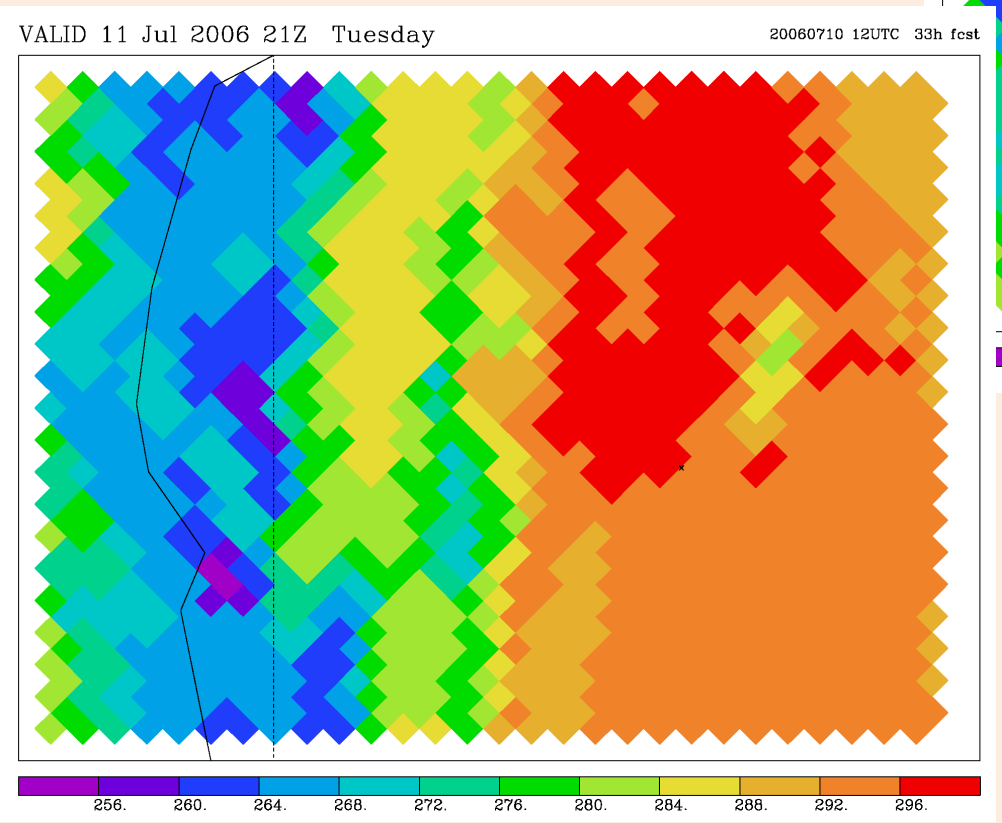
Warming around San Juan
(denoted by an "x" sign)
~ 16 K in 9 hours



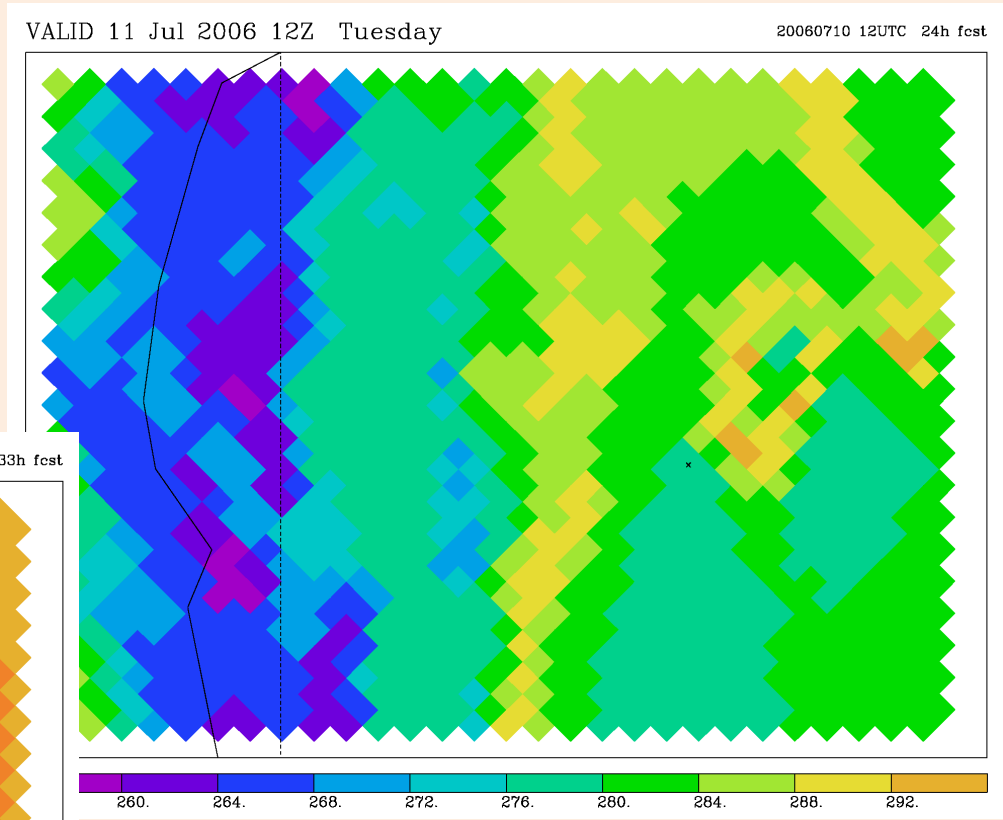
33 h fcst

Cut-cell Eta

Lowest layer T



33 h fcst



24 h fcst

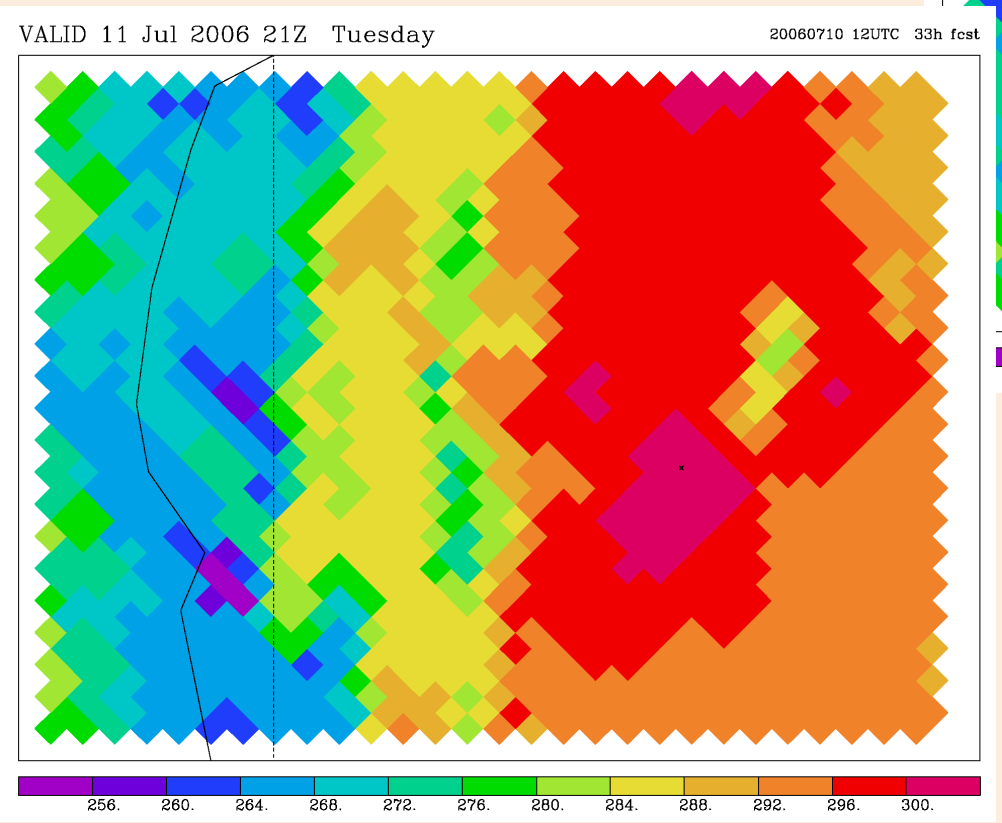
Warming around San Juan (denoted by an "x" sign)
> 16 K in 9 hours

Cut-cell code however had an error, not yet the MAAP 2017 code which would have made the impact greater

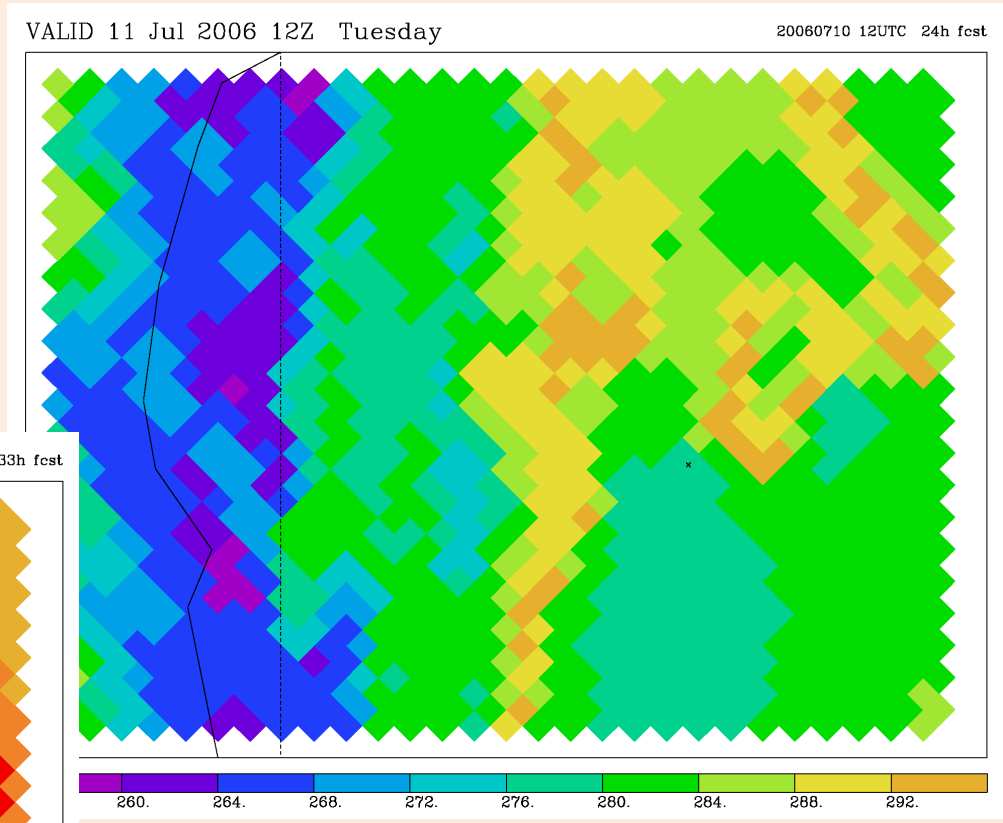
Cut-cell Eta

Van Leer type finite-volume vertical advection

Lowest layer T



33 h fcst



24 h fcst

Warming around San Juan (denoted by an “x” sign) considerably > 20 K in 9 hours !

But what can we do on climate time scales ?

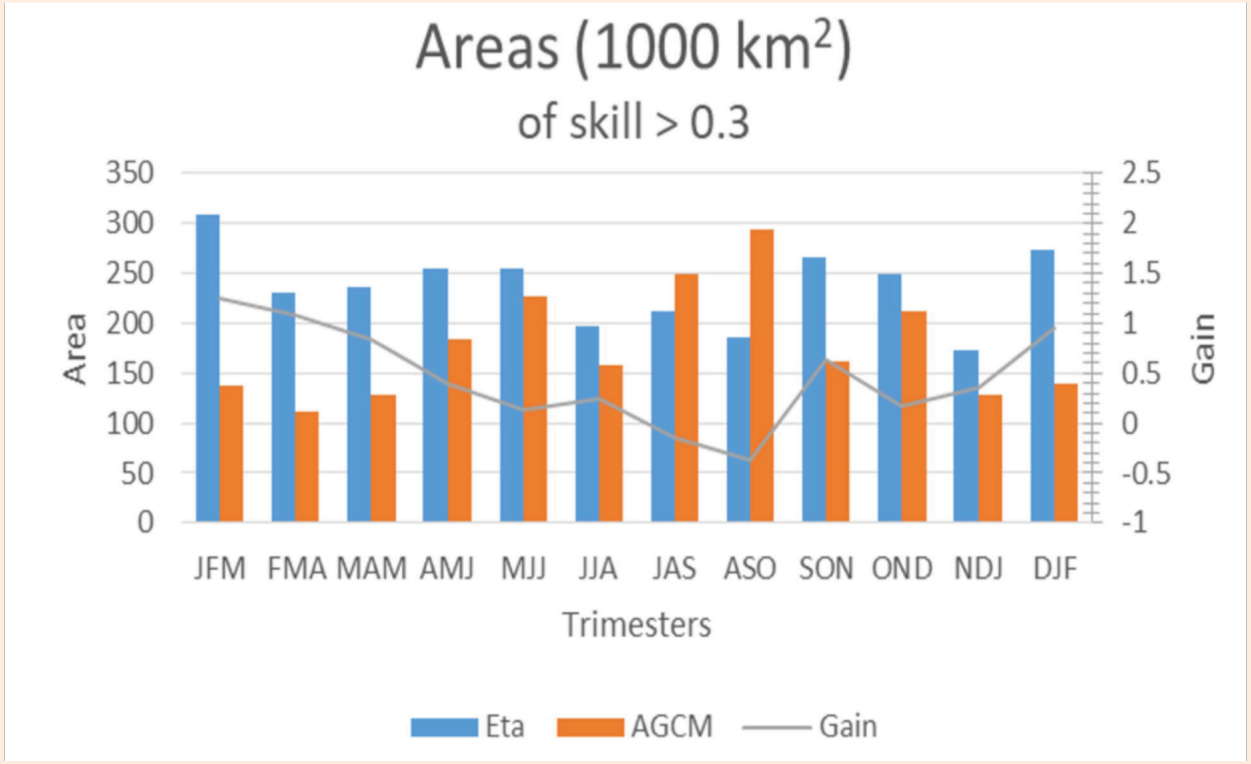
Shukla J. 1998: Predictability in the midst of chaos: A scientific basis for climate forecasting.
Science 282: 728-731.

Ten-year seasonal climate reforecasts over South America using the Eta Regional Climate Model

SIN CHAN CHOU, CLAUDINE DERECZYNSKI, JORGE LUÍS GOMES, JOSÉ FERNANDO PESQUERO, ANA MARIA H. DE AVILA, NICOLE C. RESENDE, LUÍS FELIPE ALVES, RAMIRO RUIZ-CÁRDENAS, CARLOS RENATO DE SOUZA & JOSIANE FERREIRA F. BUSTAMANTE

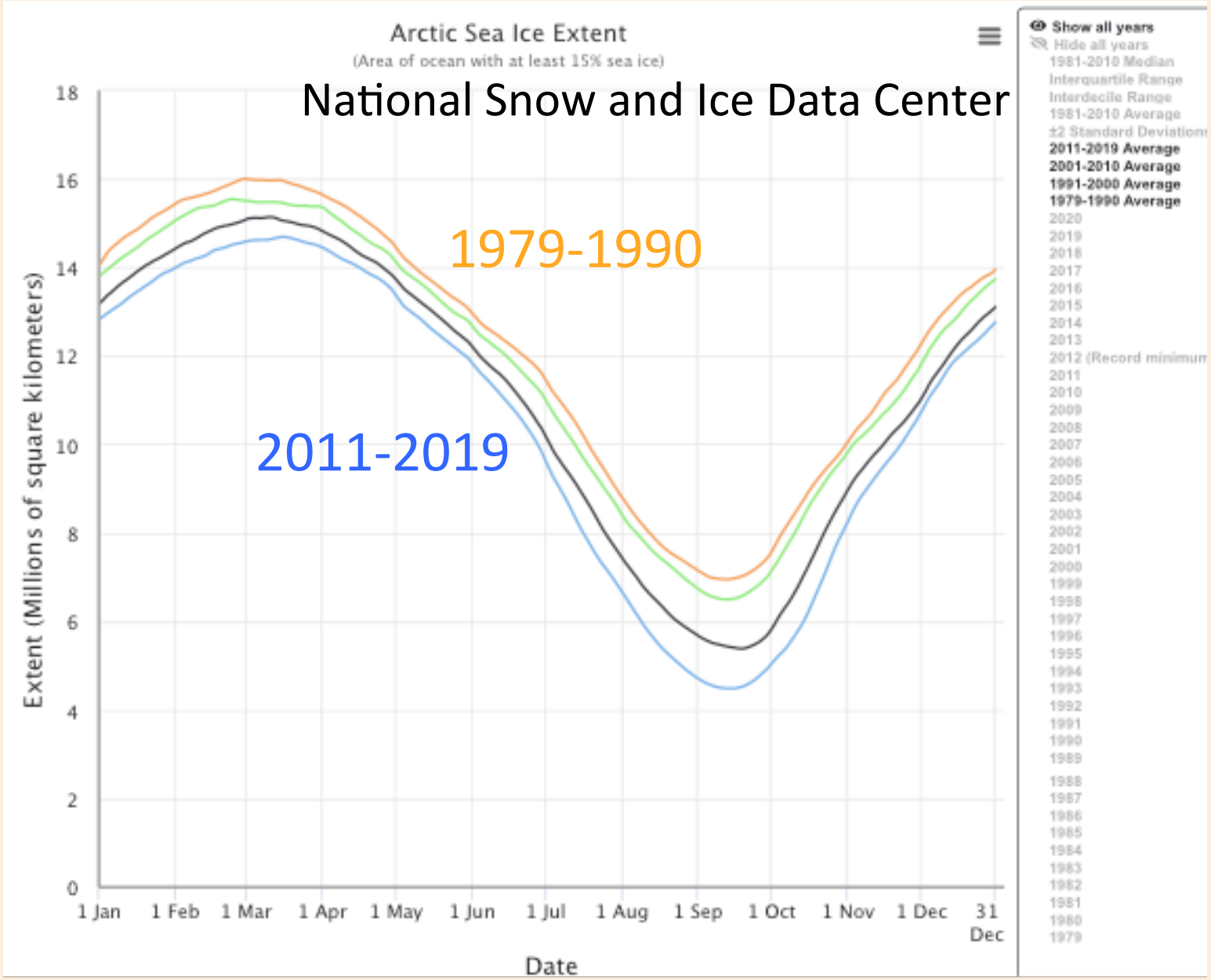
Annals of the Brazilian Academy of Sciences, 2020, 92(3)

Areas with anomaly correlation > 0.3 of 3-month ensemble forecasts of the CPTEC global climate model and nested Eta driven by LBCs of global model ensemble members

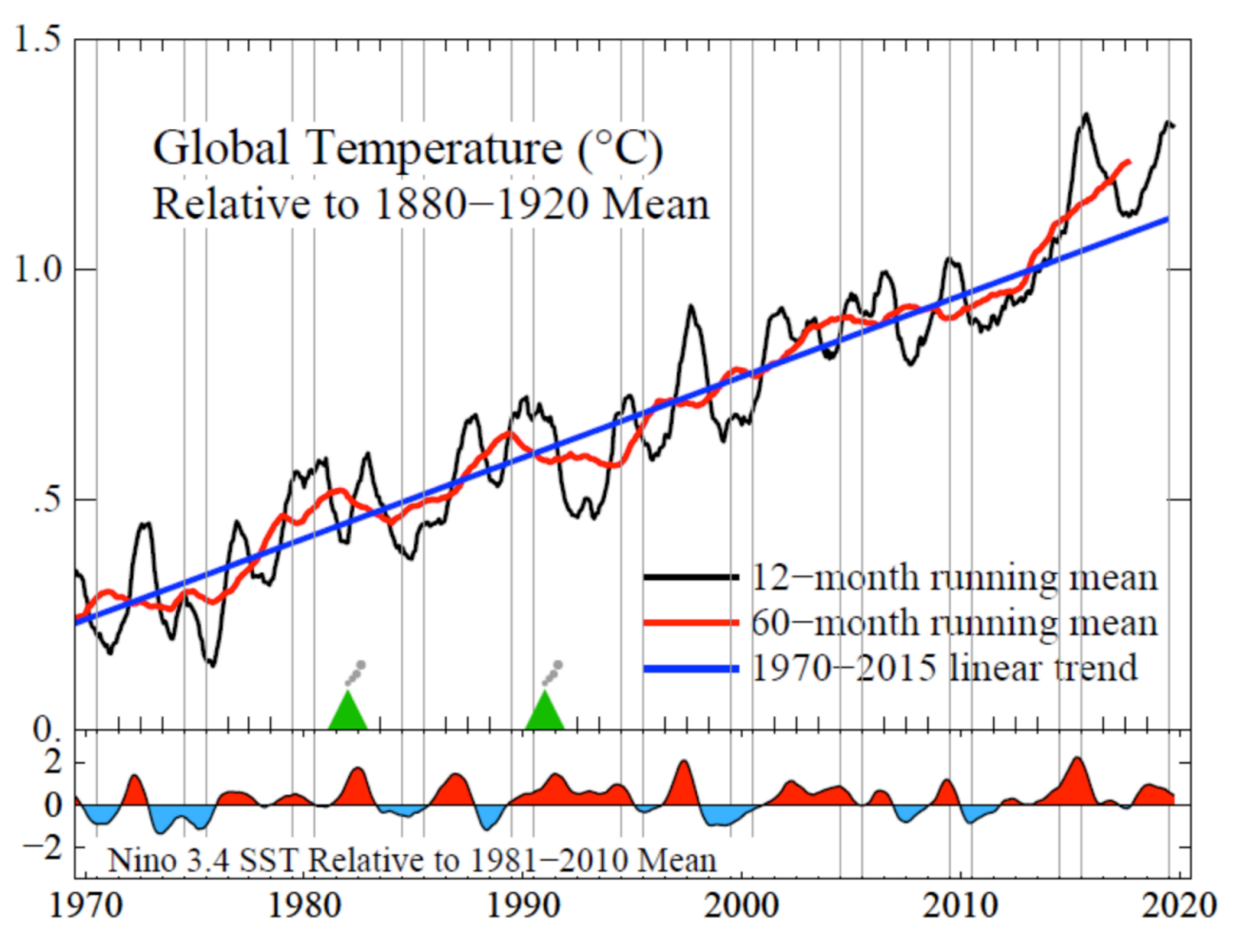


Climate change time scales?

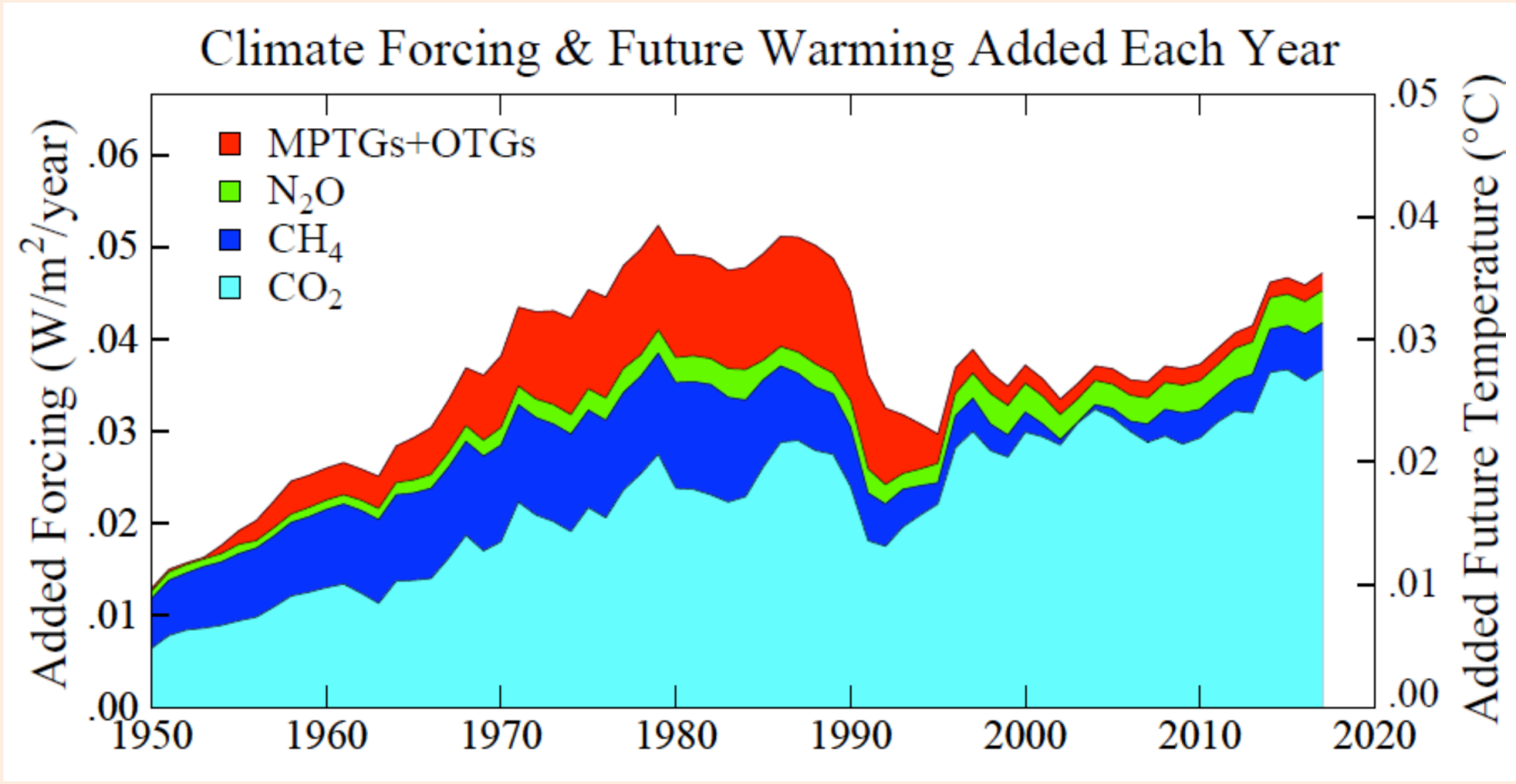
We have global warming in progress



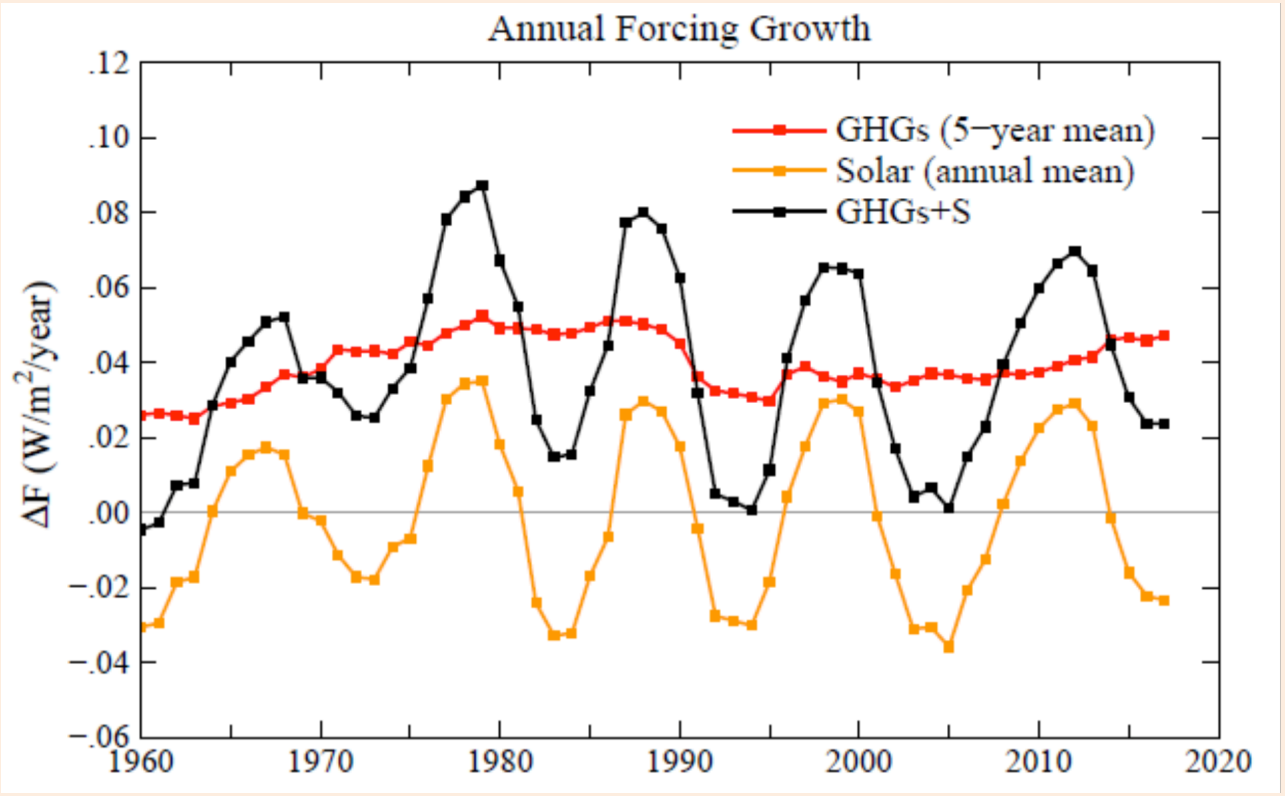
James Hansen
Communication,
October 14,
2020:



"Accelerated Global Warming"



Annual growth of GHG climate forcing (red: trace gases, mainly CFCs)



Total GHG + Solar climate forcing has been decreasing in the last five years

Large unmeasured forcing: atmospheric aerosols

To balance climate system components that are measured with good accuracy, including heat content of the oceans (so called Argo floats), aerosols need attention

"Take home" message, 1:

- While performance of models at "weather" time scales, up to about 10 days, improved to an impressive degree, there is room for further progress ! Some reasons to believe that:
    - Terrain representation in just about all models can be better than it is;
    - Finite-volume numerical cores deserve more attention;
    - Diversity of dynamical core approaches is increasing
    - . . .
- S2S (subseasonal to seasonal) time scales: useful skill ! Will surely increase. . .

“Take home” message, 2:

- Climate change time scales: Realism of “Earth system models” can only increase as availability of necessary real-world information, aerosols, more, is increased

Additional detail: James Hansen’s “Sophie’s Planet” chapters, posted online.


The end
"What a Wonderful World"