3TU.AMI Applied Mathematics Institute, Big Data meeting, 8 April 2016

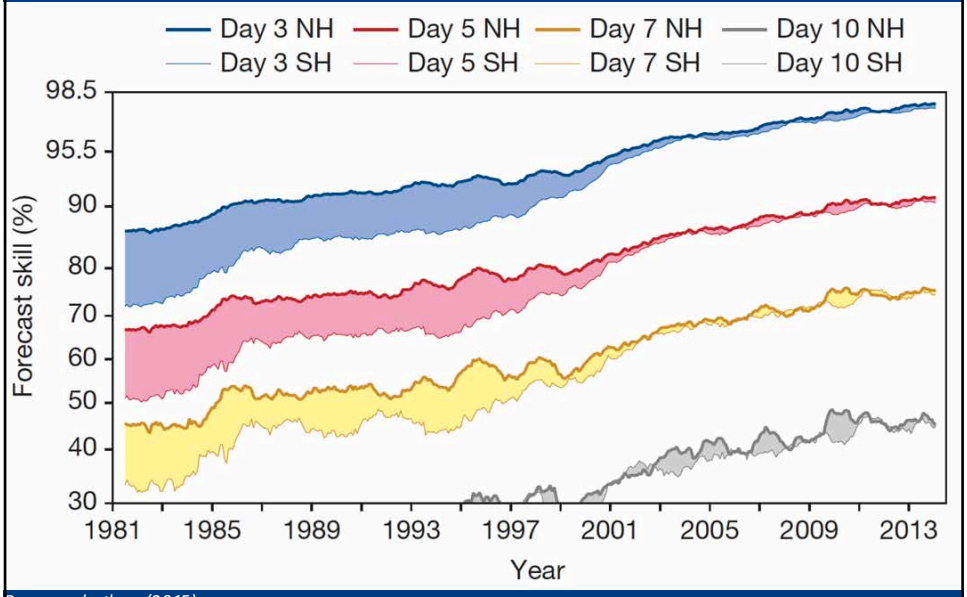
Ice sheets and climate

from hindcast to forecast

Michiel van den Broeke

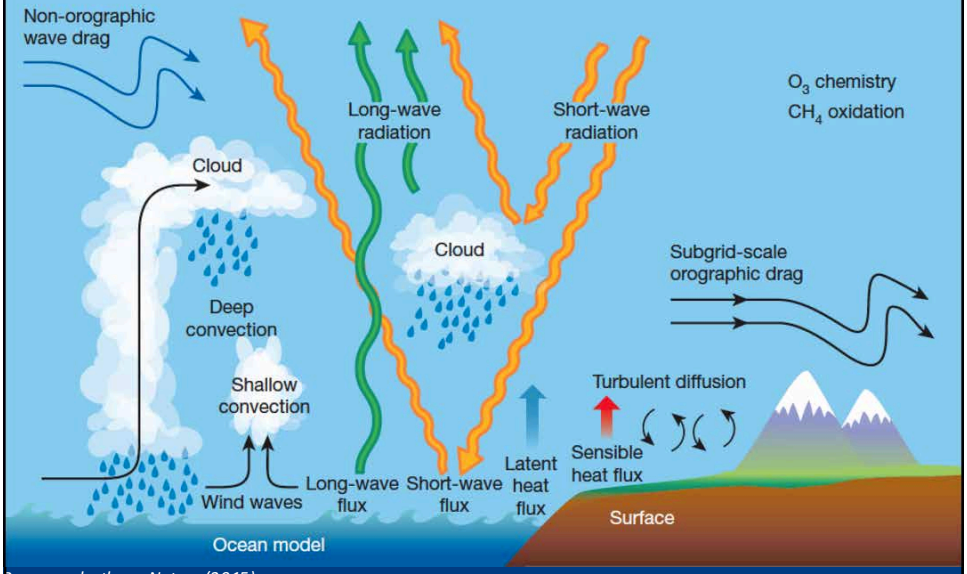
Utrecht University, Institute for Marine and Atmospheric Research (IMAU)

A quiet revolution



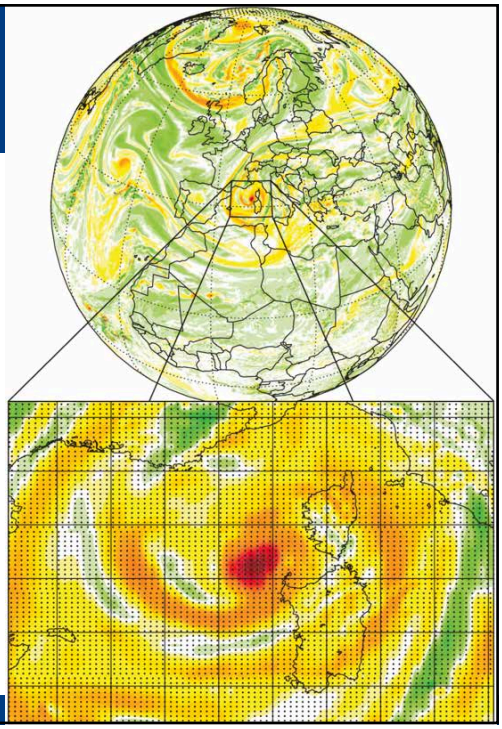
Bauer and others (2015)

Improved physics



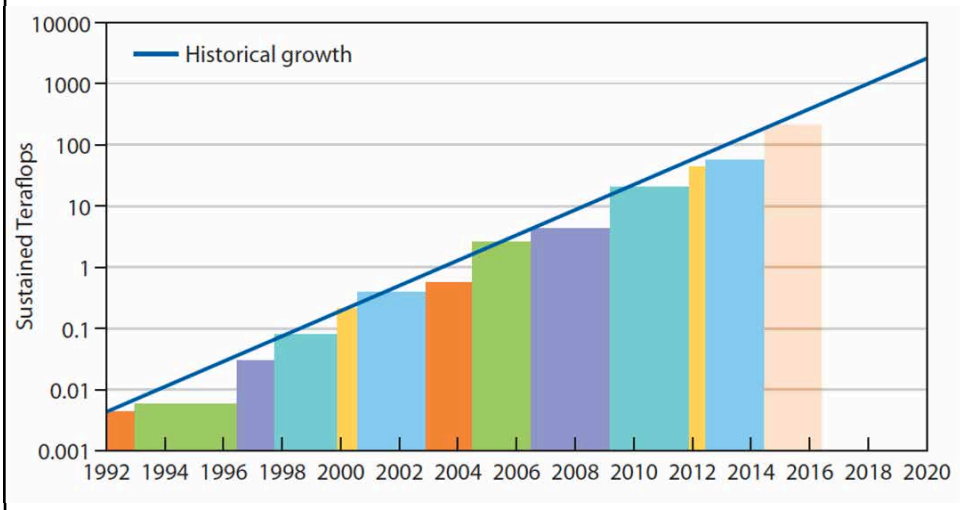
Bauer and others, Nature (2015)

Higher resolution



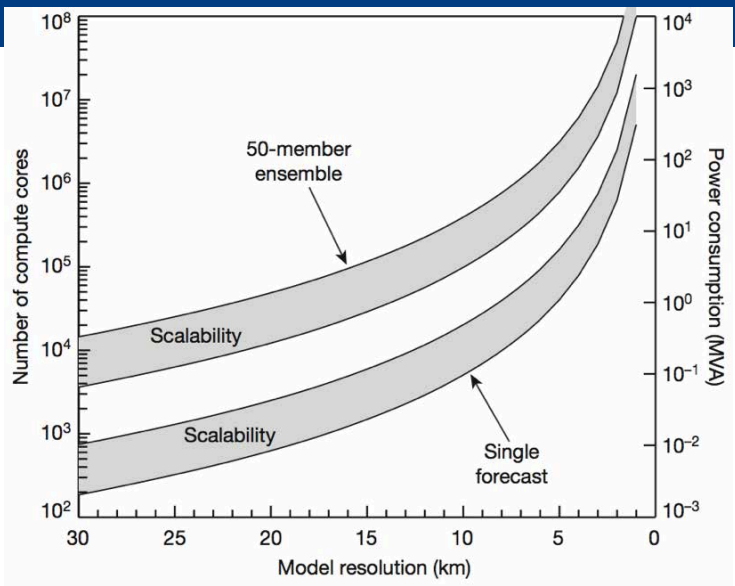
ECMWF (2012)

Improved computing power



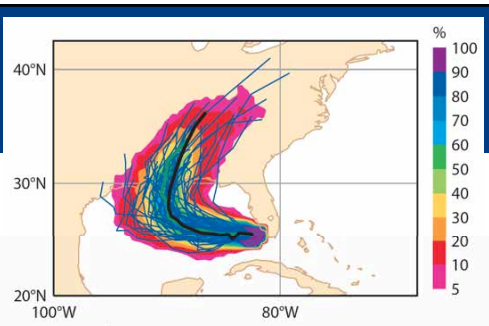
ECMWF (2015)

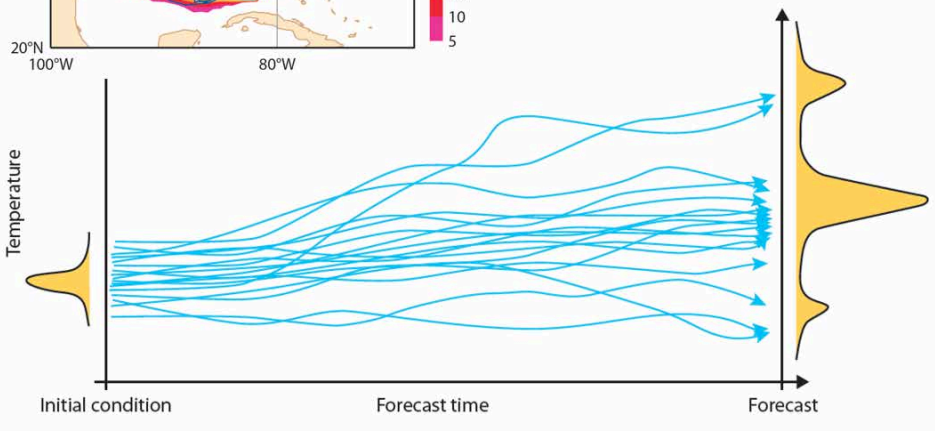
Technological challenge: power consumption



Bauer and others (2015)

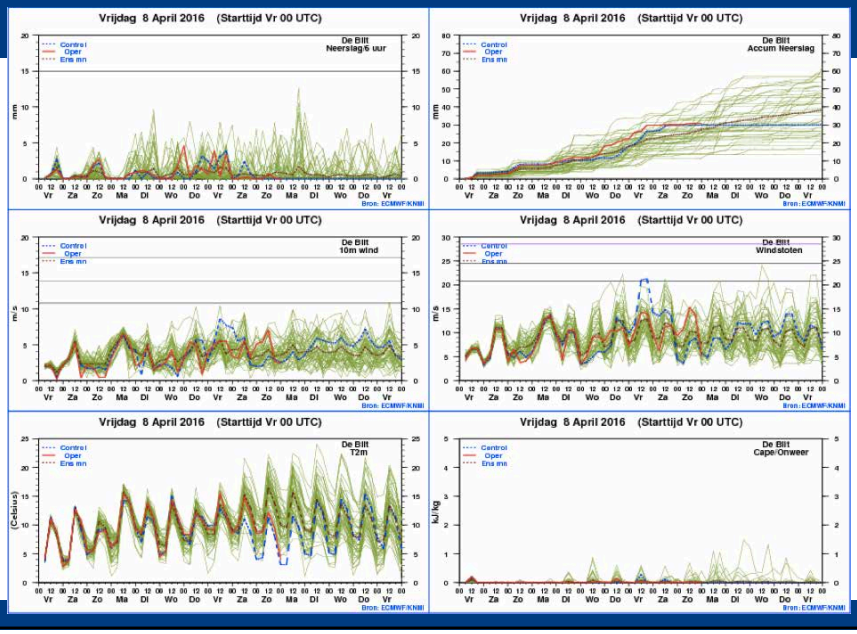
Improved uncertainty estimates (EPS)



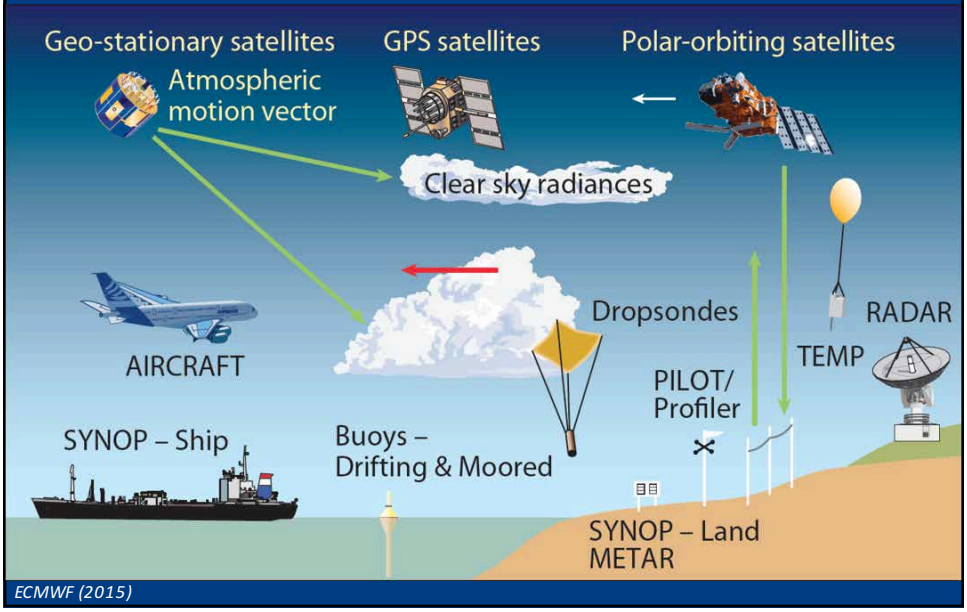


ECMWF (2015)

ECMWF 1+1+50 ensemble member prediction



Better and more observations (4DVAR)

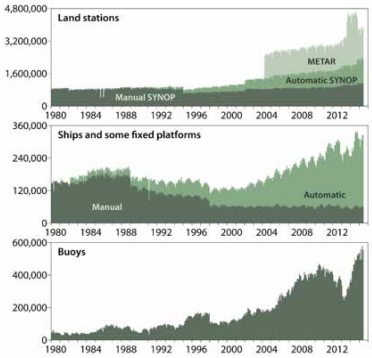


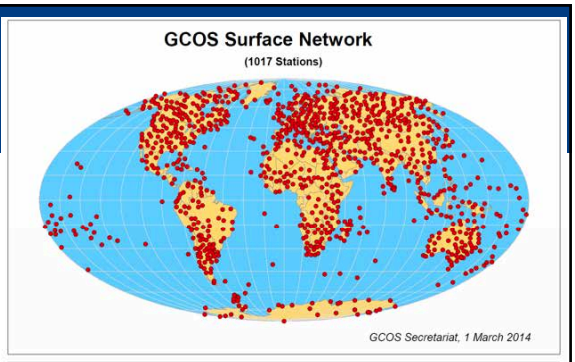
ECMWF (2015)

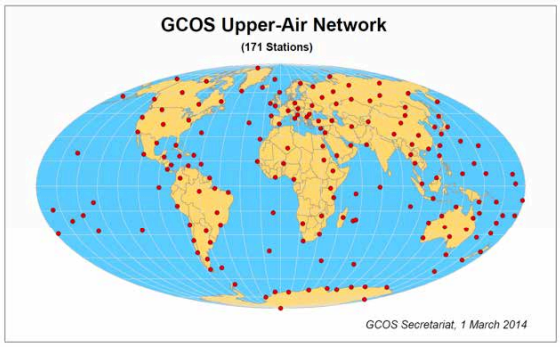
Better observations

- accurate under wide range T, p
- fast response (small sensor)
- accurate (good ventilation, small radiation error)
- humidity defroster
- GPS wind finding
- strong (low T) but environmental friendly battery
- expensive….

More observations







WMO (2015)

Atmospheric reanalyses

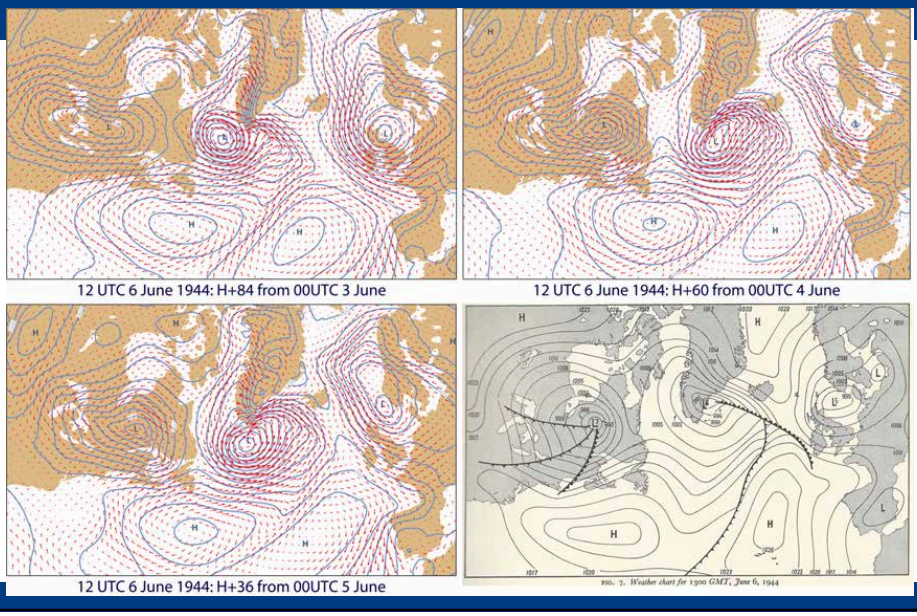
Goal:
To reconstruct the 4D state of the global atmosphere as far back in time as possible

Method:
Use latest version of prediction model and data assimilation and all available observations

Summary of Atmospheric Reanalysis products

Name	Source	Domain	Period of Record	available timestep(s)	available resolution	available format(s)	Model Resolution	scheme & model vintage
Arctic System Reanalysis (ASR)	Byrd Polar Research Center, The Ohio State University/ David Bromwich,NCAR,CIRES,U Illinois	Arctic	2000/01 to 2012/12	Sub-daily, Monthly	30 km; 71 levels; 10hPA top, 10 km	netCDF	30 km and 10 km	WRF-VAR
Climate Forecast System Reanalysis (CFSR)	NCEP	Global	1979/01 to 2011/01	Sub-daily, Monthly	.5°x.5° & 2.5°x2.5°, 0.266 hPA top	GRIB	T382 x 64 levels	3DVAR | 2009
ERA-15	ECMWF	Global	1979/01 to 1993/12	Sub-daily, Monthly	T106, 2.5 x 2.5	GRIB	T106 (1.125)	
ERA-20C: ECMWF's atmospheric reanalysis of the 20th century (and comparisons with NOAA's 20CR)	ECMWF	Global	1900/01 to 2011/01	Sub-daily, Daily, Monthly	~ 125km; 160 x 320; 91 model levels/ 37 pressure levels / 16 potential temperature levels, and the 2 PVU potential vorticity level	netCDF, GRIB		4DVAR
ERA-Interim	ECMWF	Global	1979/01 to 2016/01	Sub-daily, Daily, Monthly	0.75°x0.75°x60 lev 0.1 hPA top	netCDF, GRIB	T255, 60 levels	4DVAR | 2006
ERA40	ECMWF	Global	1957/09 to 2002/08	Sub-daily, Monthly	2.5°x2.5° / 1.125°x1.125°; 60 levels 0.1 hPA top	netCDF, GRIB	T159, 60 levels	3DVAR | 2004
JRA-25	Japanese Meteorological Agency	Global	1979/01 to 2004/12	Sub-daily, Monthly	1.125x1.125/2.5x2.5; 0.4 hPA top	GRIB	T106, 40 levels	3DVAR | 2004
JRA-55	Japanese Meteorological Agency	Global	1957/12 to 2016/01	Sub-daily, Monthly	T319 x 60 levels, 0.1 hPA top	GRIB	T319 x 60 levels	4DVAR | 2009
NASA MERRA	NASA	Global	1979/01 to 2013/01	Sub-daily, Monthly	0.5° x 0.667° x 72 , 0.01 hPA top	netCDF, HDF	0.5° x 0.667° x 72	GEOS IAU | 2009
NCEP NARR	NCEP	North America	1979/01 to 2016/04	Climatology, Sub-daily, Monthly	32km	GRIB	32km x 45 eta	3DVAR | 2003
NCEP Reanalysis (R2)	NCEP,DOE	Global	1948/01 to 2007/04	Sub-daily, Daily, Monthly	2.5°x2.5° 28 levels 3 hPA top	netCDF, GRIB	T62 28 levels	3DVAR | 2001
NCEP-NCAR (R1): An Overview	NCEP,NCAR	Global	1948/01 to 2015/01	Sub-daily, Daily, Monthly	2.5°x2.5°; 3 hPA top	netCDF, GRIB	T62 - 28 levels	3DVAR | 1995
NOAA 20th-Century Reanalysis, Version 2 and 2c	NOAA ESRL,CIRES CDC / Gil Compo	Global	1850/12 to 2014/12	Sub-daily, Daily, Monthly	2°x2°, 28 levels 10 hPA top	netCDF, GRIB	T62 28 levels	Ensemble Kalman Filter | 2009

Reconstruction of meteorology during D-day



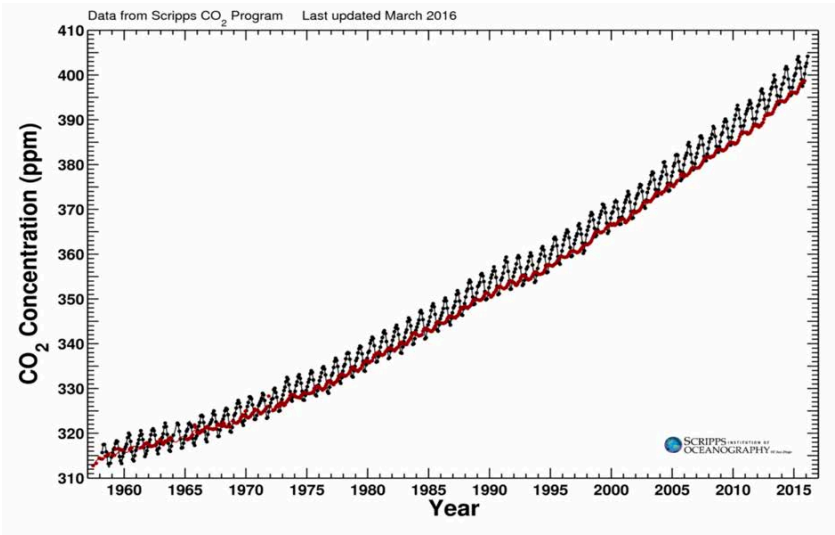
12 UTC 6 June 1944: H+84 from 00UTC 3 June

12 UTC 6 June 1944: H+60 from 00UTC 4 June

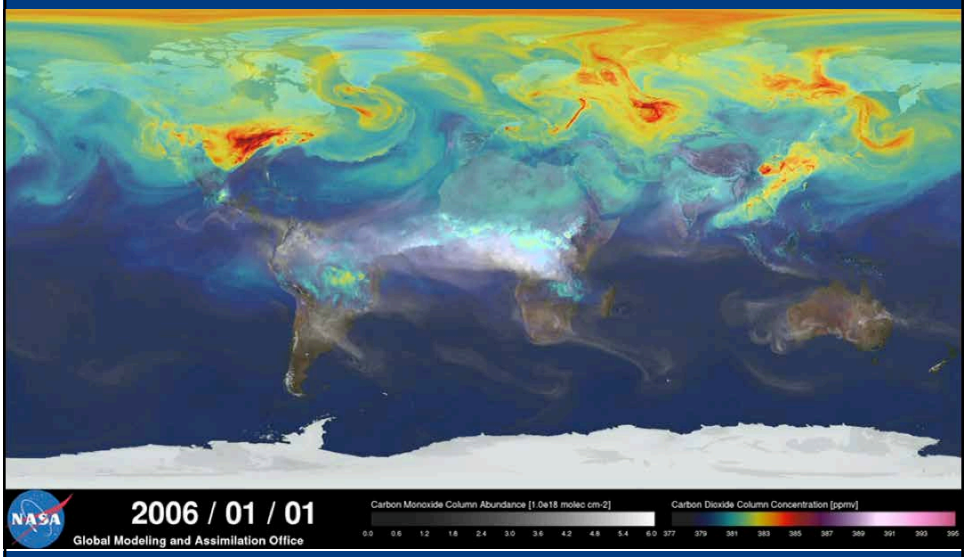
12 UTC 6 June 1944: H+36 from 00UTC 5 June

FIG. 7. *Weather chart for 1300 GMT, June 6, 1944*

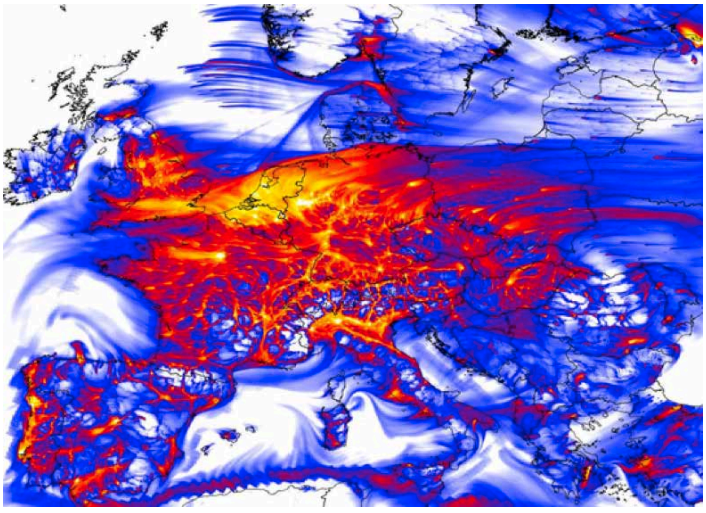
CO_2 observations from Hawaii and South Pole



Atmospheric CO_2 concentration



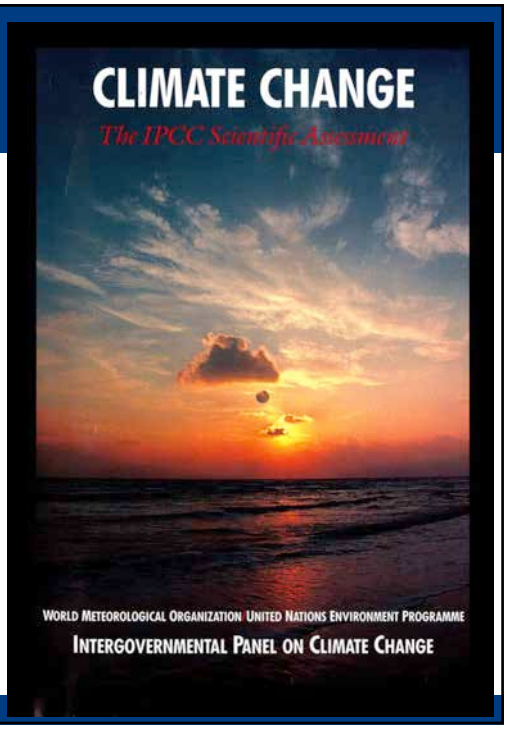
Chemistry transport models



NO_2

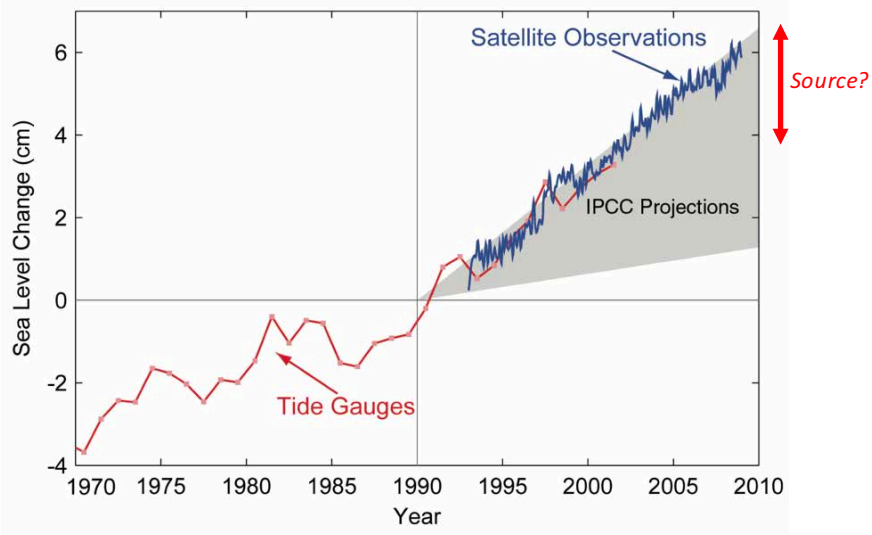
Chimere.fr

IPCC (1990)
First Assessment Report



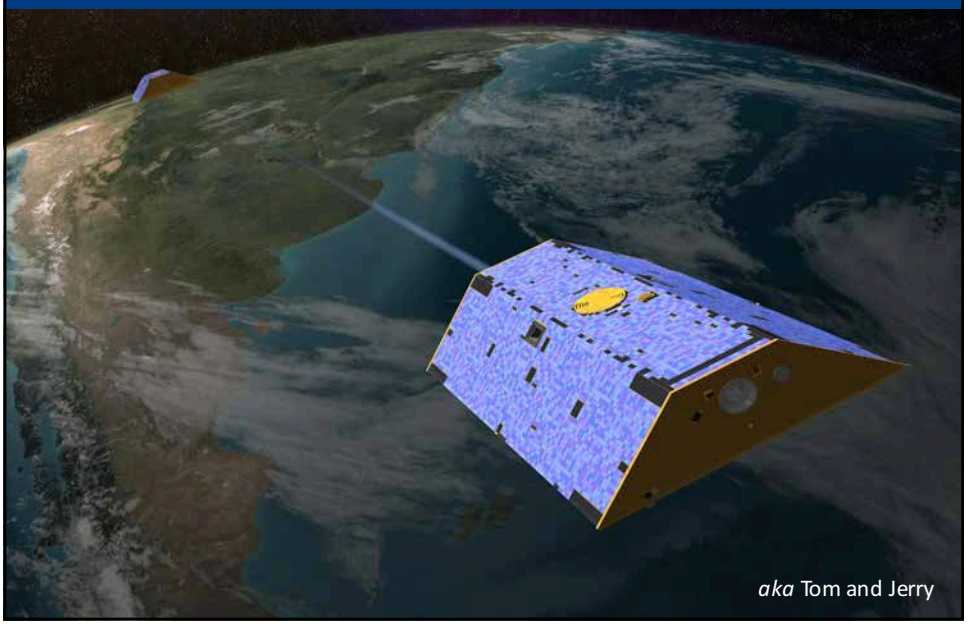
IPCC, 1990

Predicted vs. observed sea level change

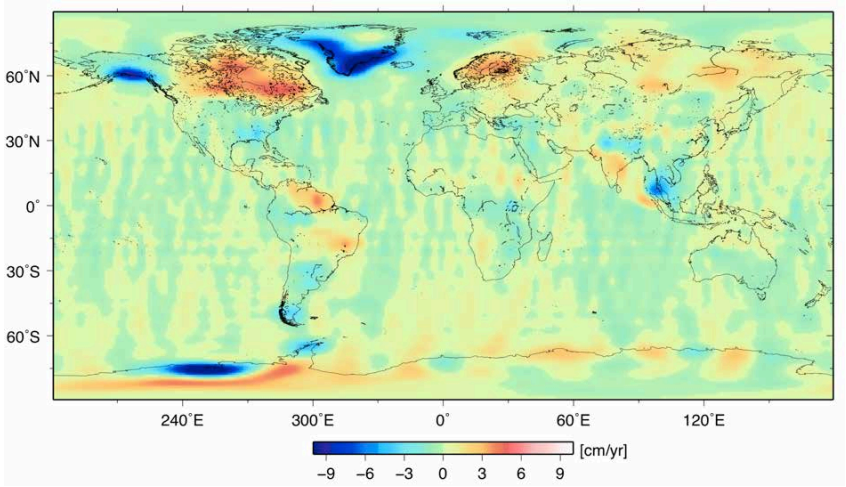


The Copenhagen Diagnosis, 2009

Gravity Recovery And Climate Experiment (GRACE)



GRACE mass trends (2003-2008)

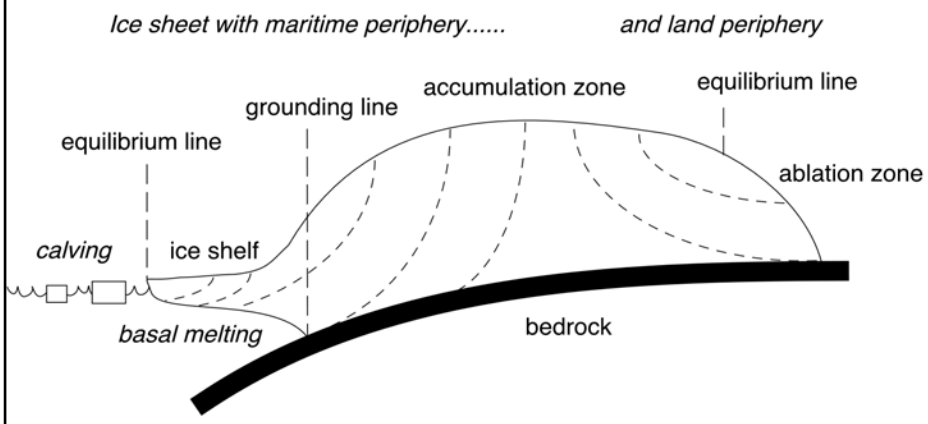


Courtesy: Bert Wouters

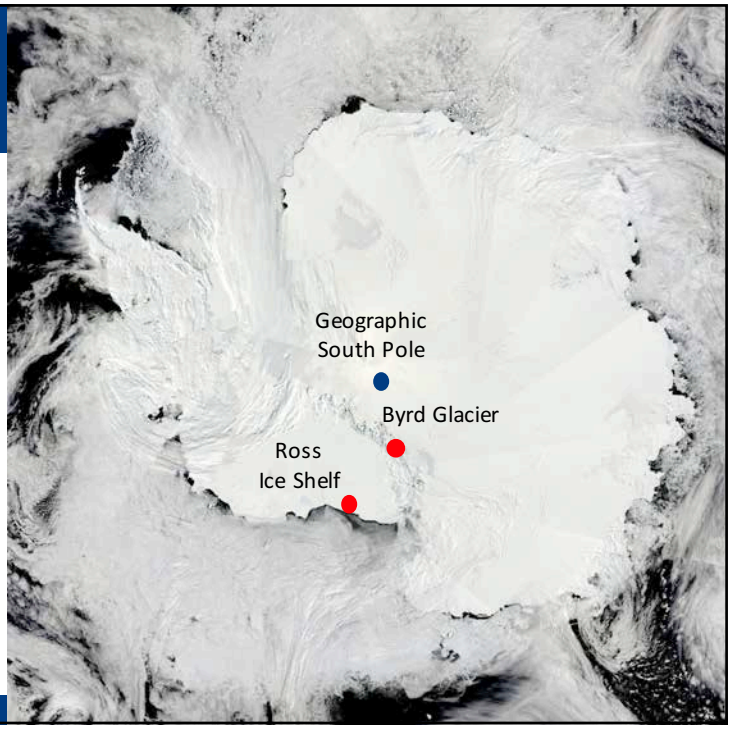
Sea level rise: potential contributions from land ice

Estimated	Antarctica	Greenland	All mountain glaciers
Area (10^6 km^2)	12.3	1.7	0.5
Mean thickness (m)	2008	1706	100-260
Volume (10^6 km^3)	24.7	2.9	0.05-0.13
Potential sea level rise (m)	**56.6**	**7.3**	**0.15-0.37**

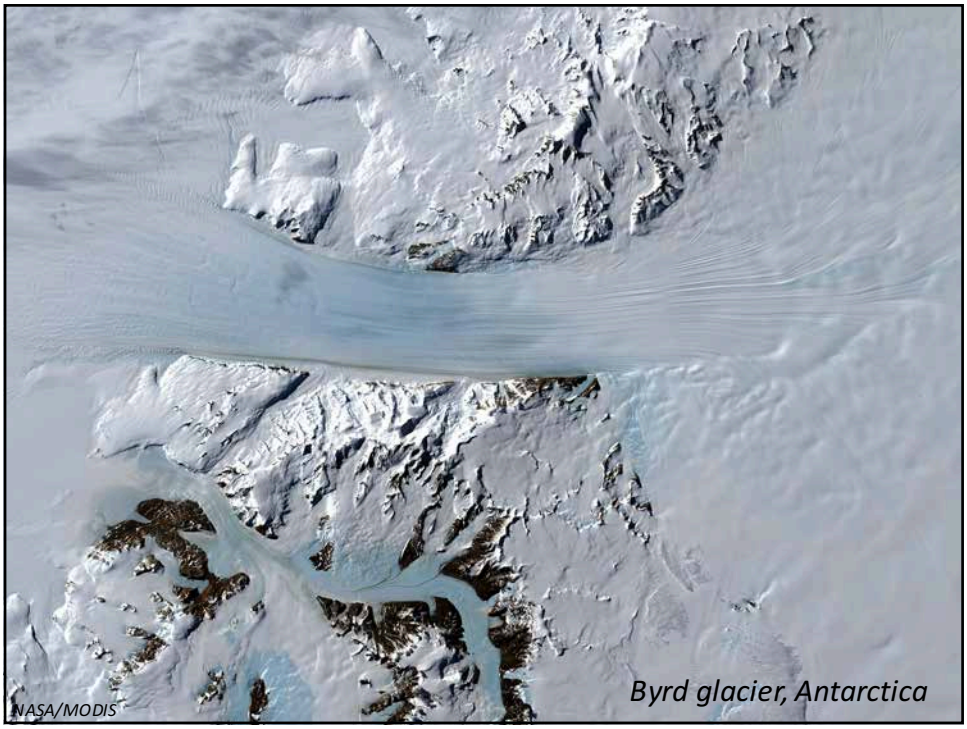
How ice sheets work



Antarctica



NASA/MODIS



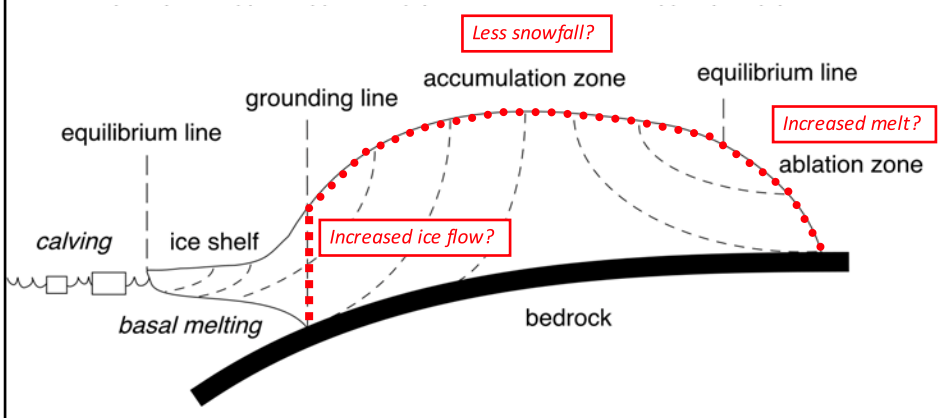
NASA/MODIS

Byrd glacier, Antarctica

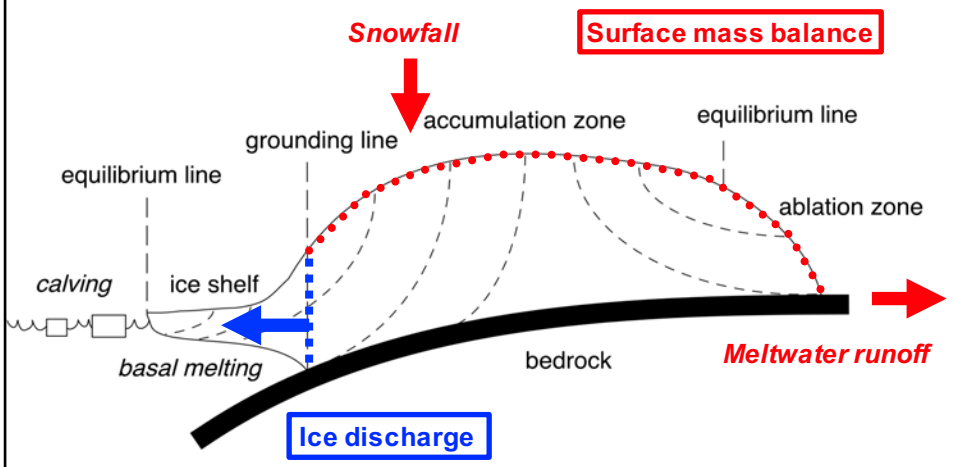

R/V Polarstern (Germany)
Photo: AWI


Calving of giant iceberg from Ross Ice Shelf, Antarctica
NASA/MODIS

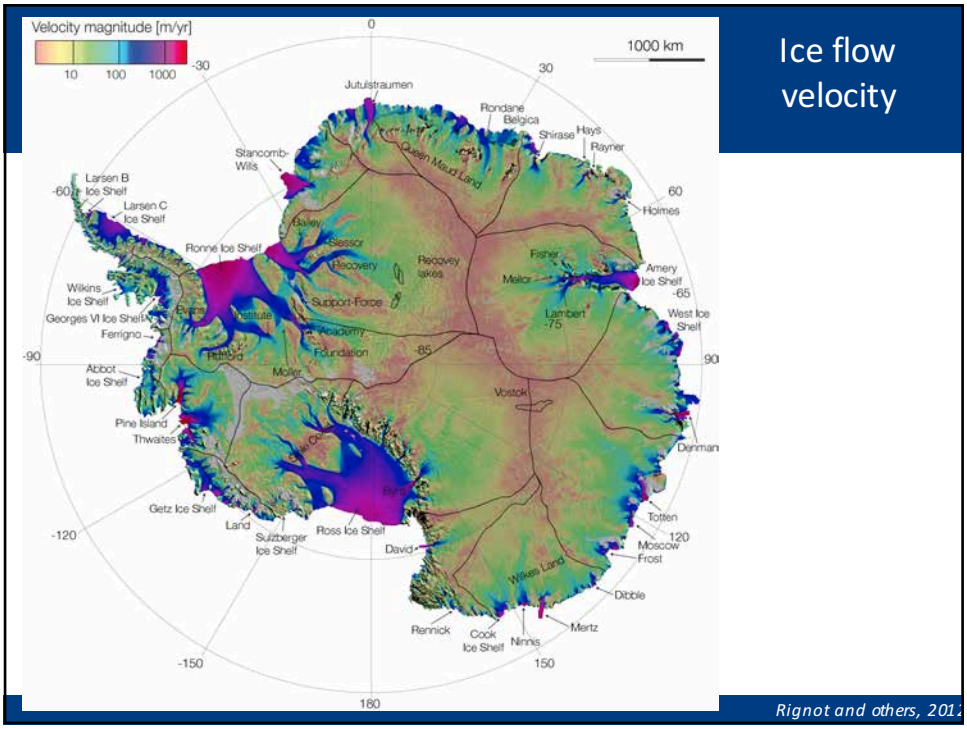
What causes the mass loss?



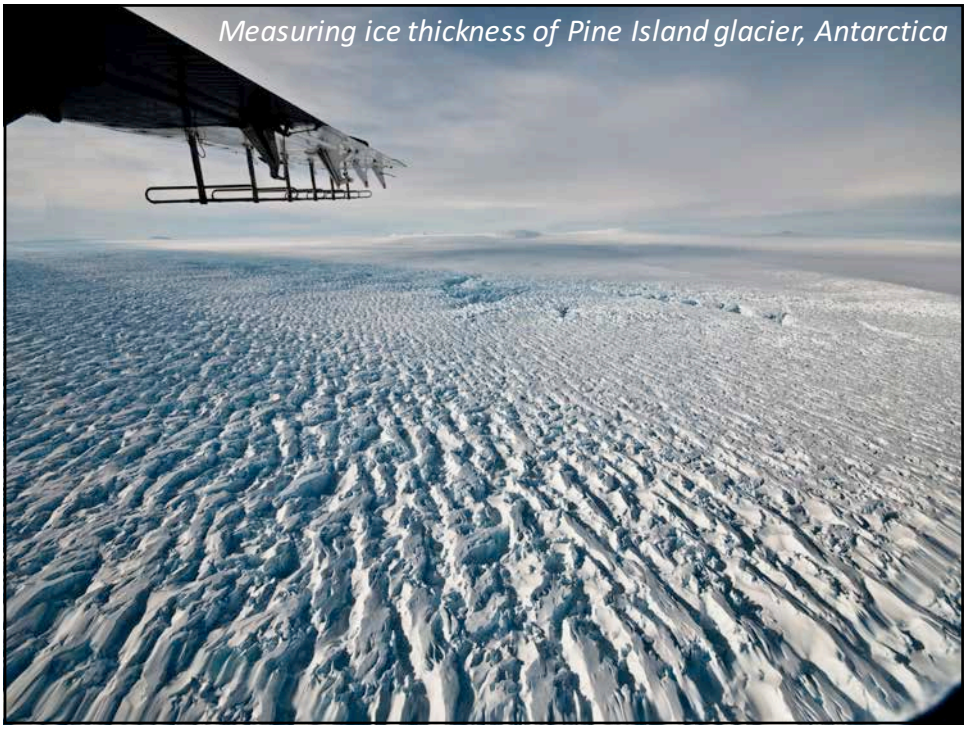
Ice sheet mass balance

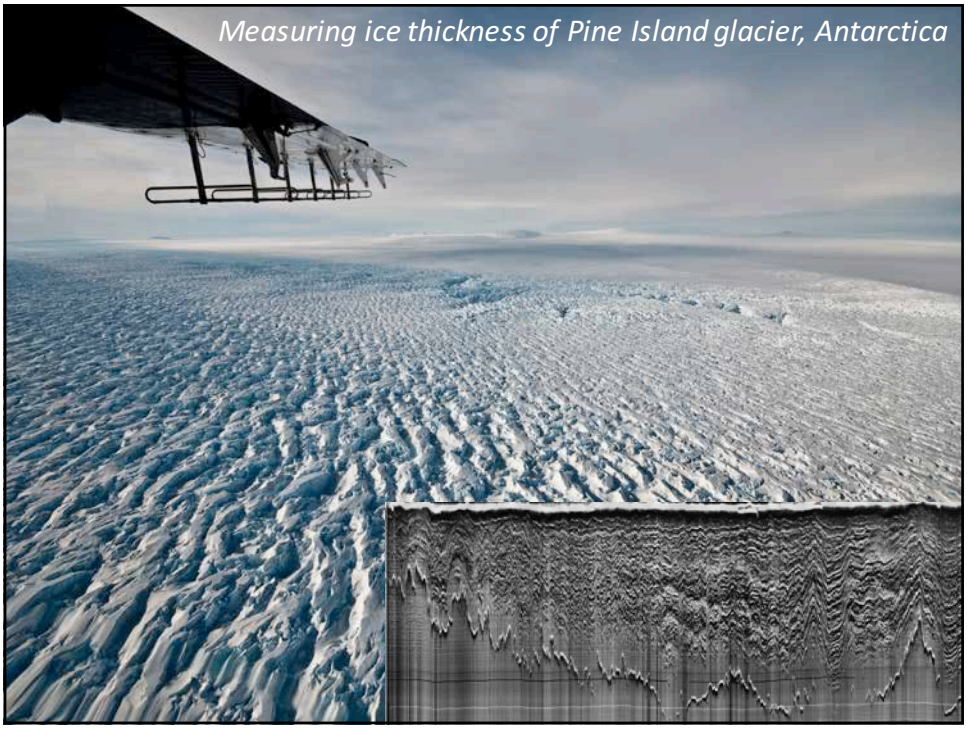


Ice flow velocity



Rignot and others, 201

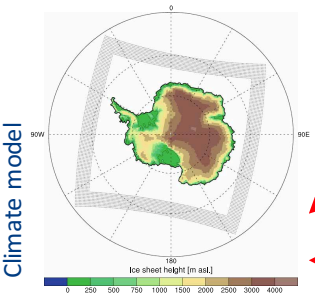

Measuring ice thickness of Pine Island glacier, Antarctica


Measuring ice thickness of Pine Island glacier, Antarctica

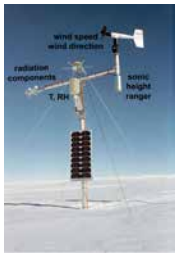
Surface mass balance: combining models with observations

Remote sensing

Climate model

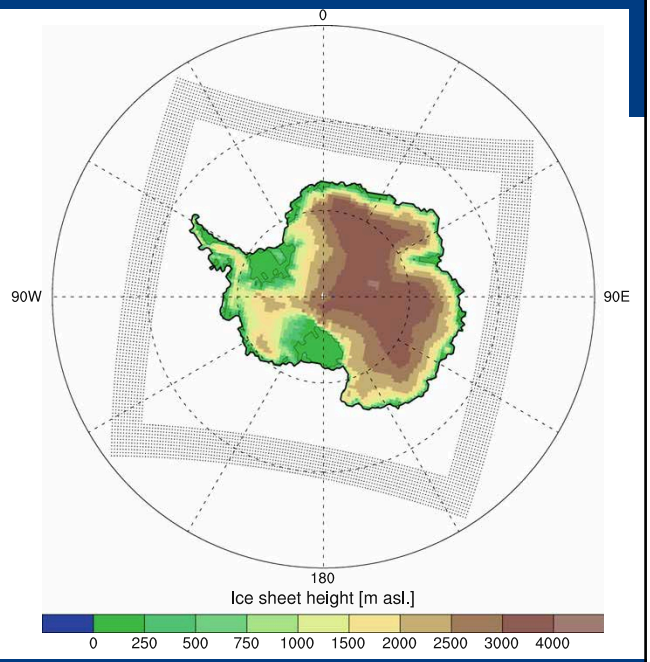


Evaluation
Calibration
Spatial/temporal extension

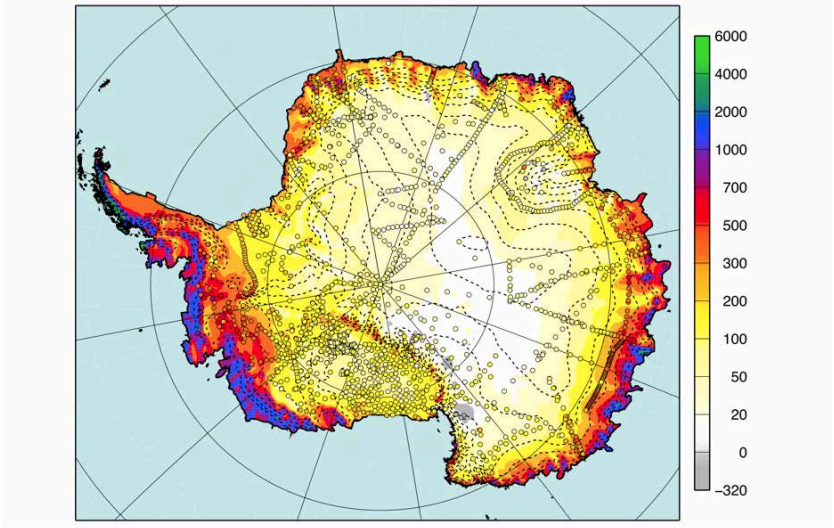


In situ observations

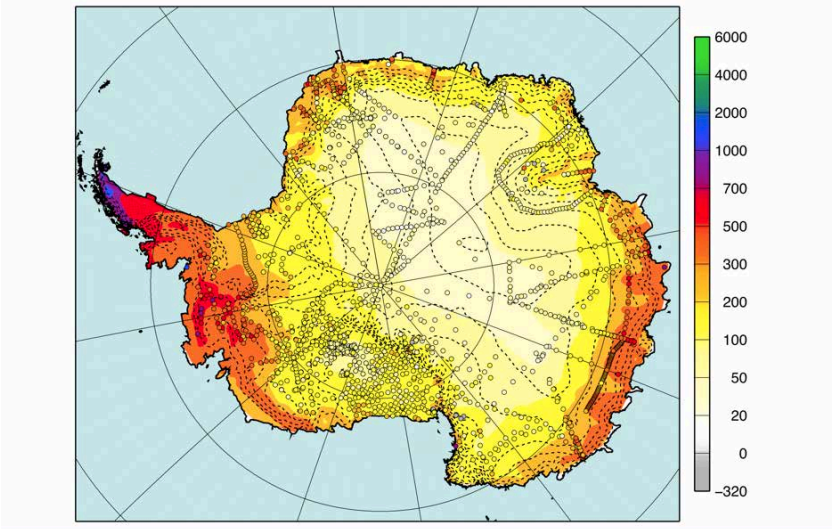
Regional climate model RACMO2



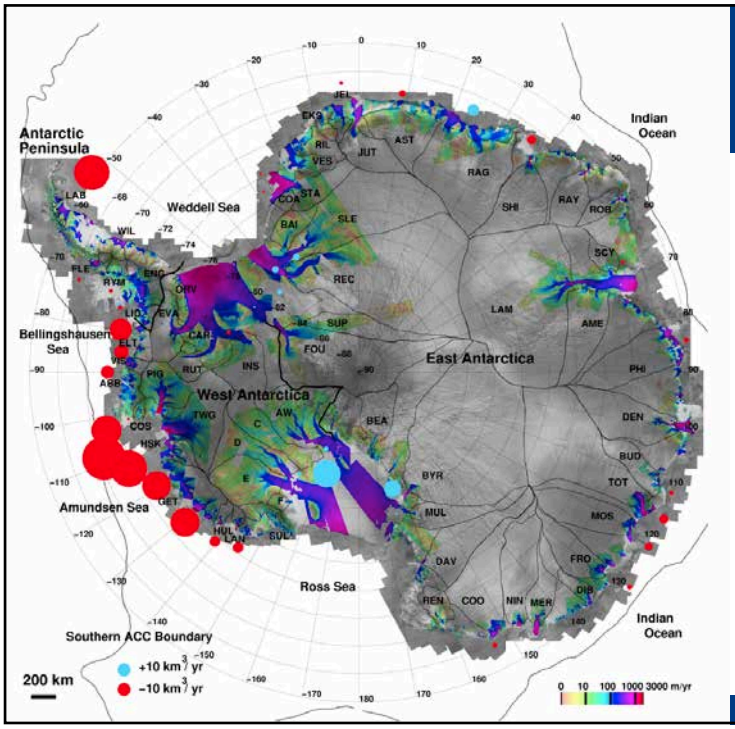
Snow accumulation map based on regional climate model (mm yr^{-1})



Snow accumulation map based on interpolation of observations (mm yr^{-1})

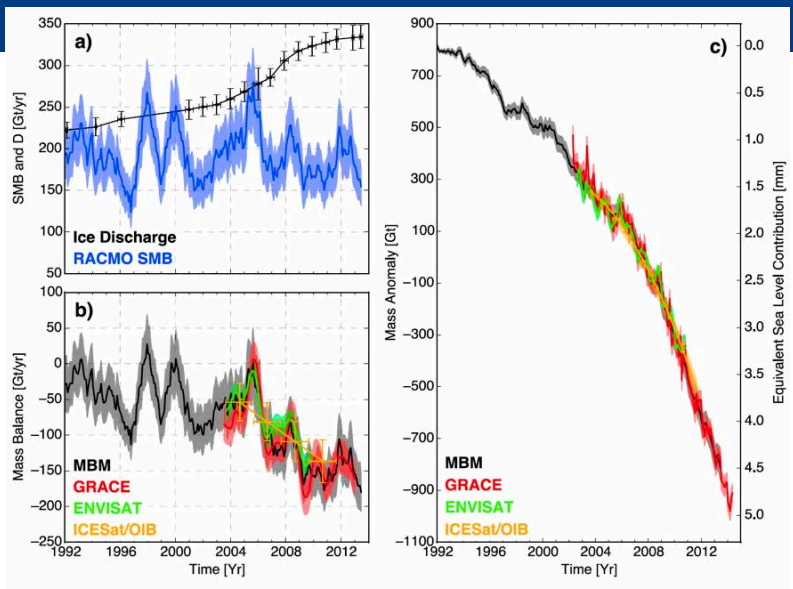


Mass loss per glacier basin



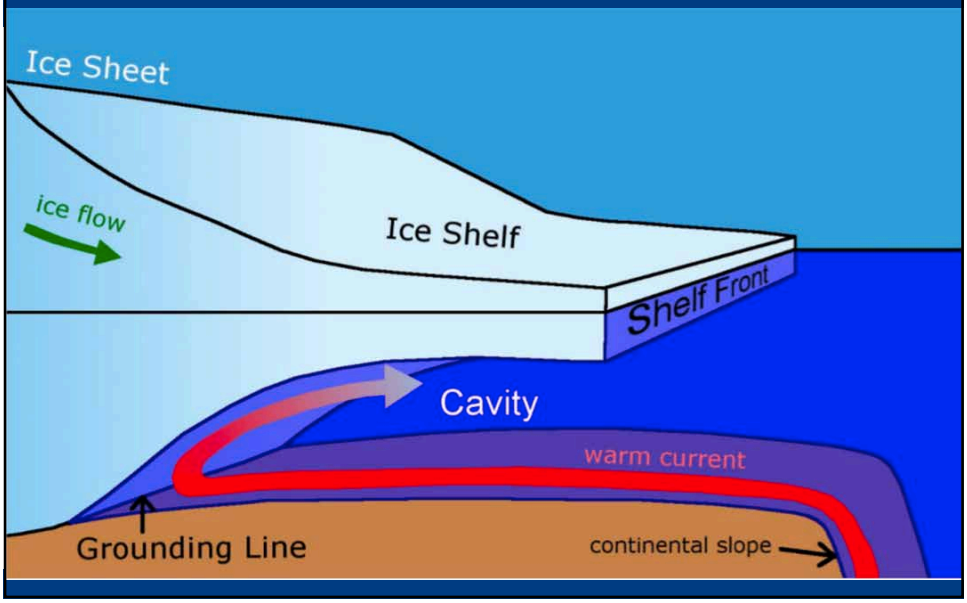
Total current mass loss: ~ 150 Gt yr^{-1}

Mass loss in West Antarctica is accelerating…

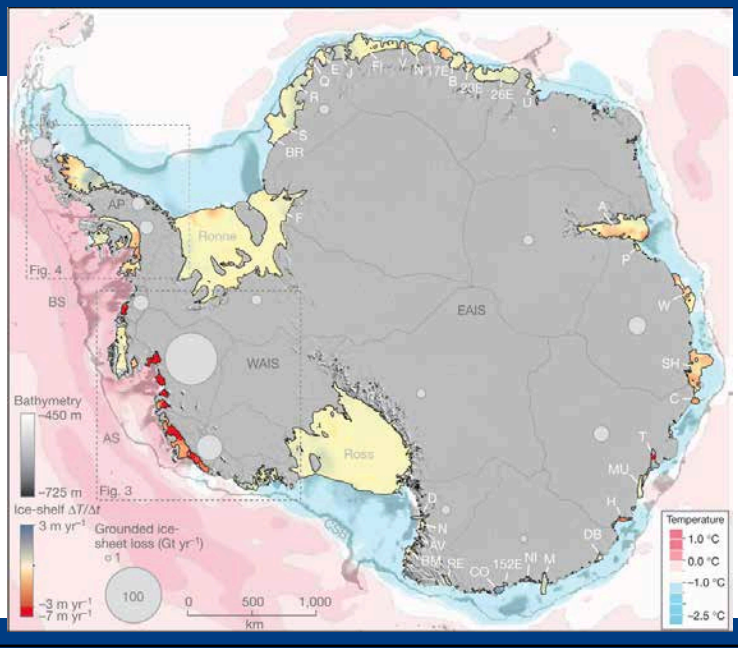


Sutterley and others, 2014

West Antarctic mass loss driven by the ocean

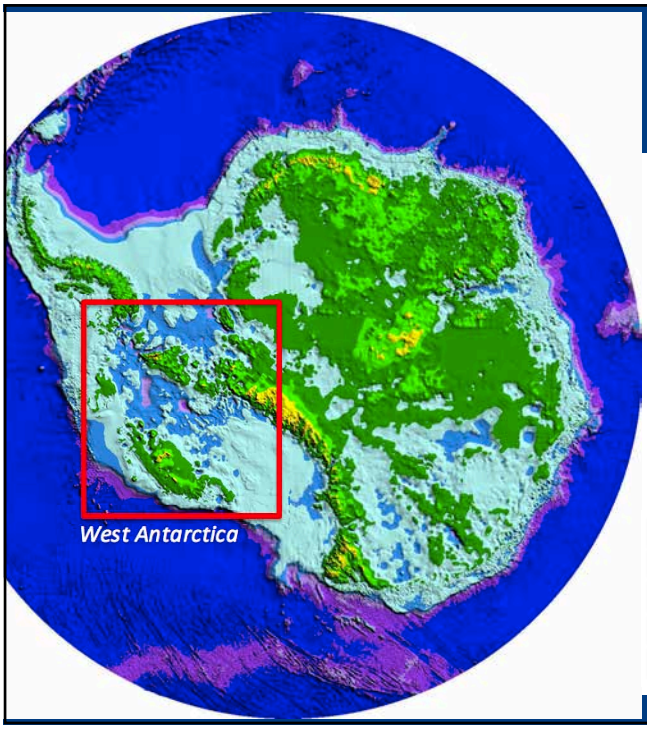


Ice shelf thinning causes loss of grounded ice



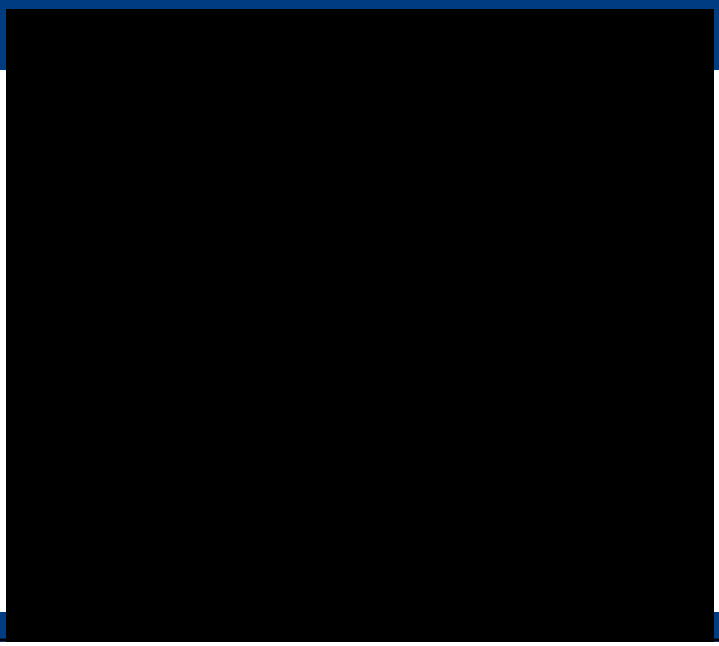
Pritchard and others, 2011

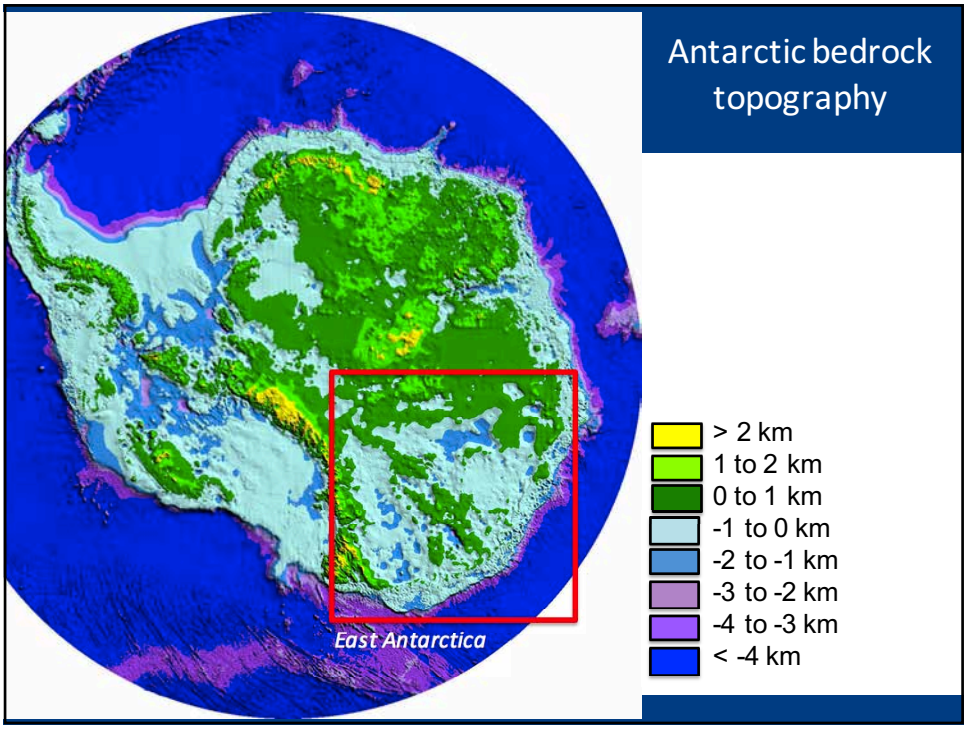
Bedrock topography

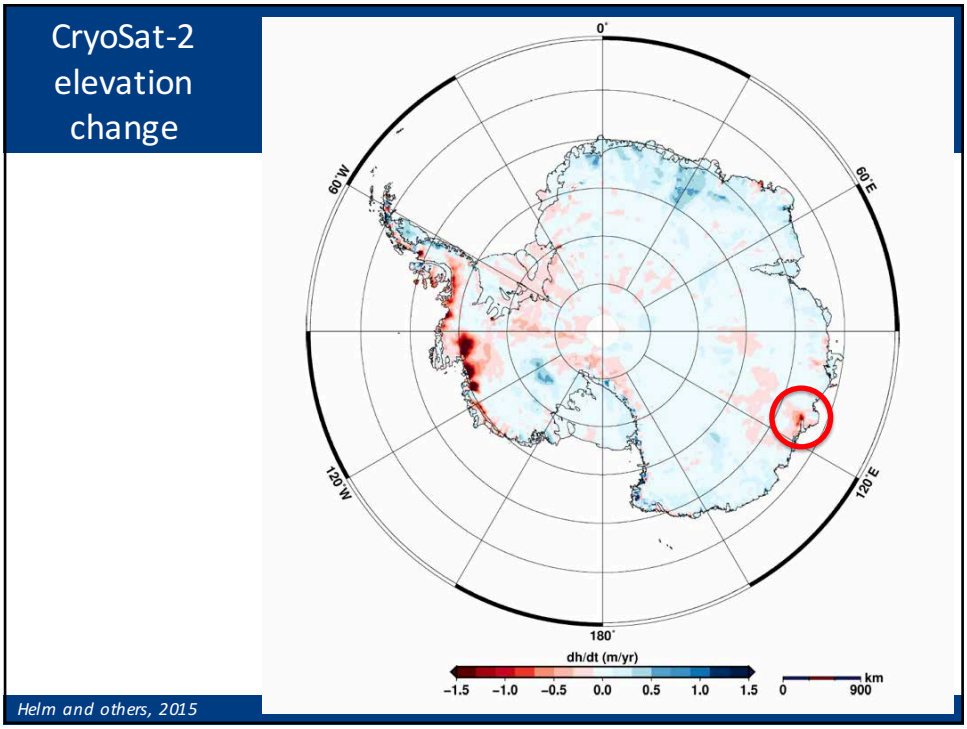


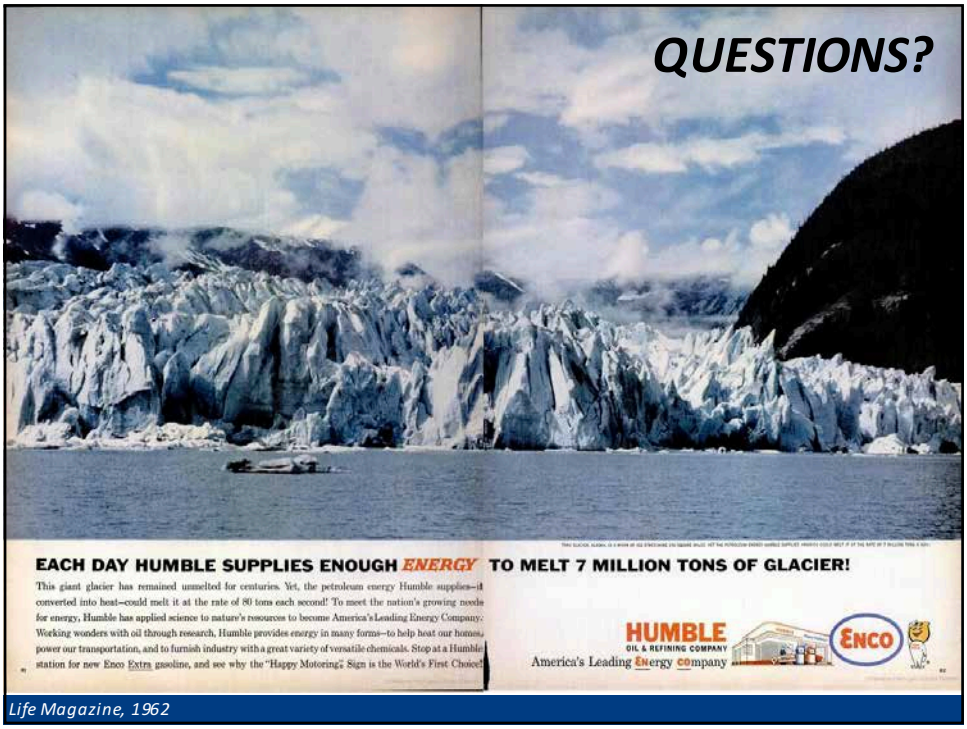
> 2 km
1 to 2 km
0 to 1 km
-1 to 0 km
-2 to -1 km
-3 to -2 km
-4 to -3 km
< -4 km

Predicted deglaciation of West Antarctica




Antarctic bedrock topography
East Antarctica
> 2 km
1 to 2 km
0 to 1 km
-1 to 0 km
-2 to -1 km
-3 to -2 km
-4 to -3 km
< -4 km


CryoSat-2 elevation change
0°
60°W
60°E
120°W
120°E
180°
dh/dt (m/yr)
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5
0 900 km
Helm and others, 2015



Life Magazine, 1962