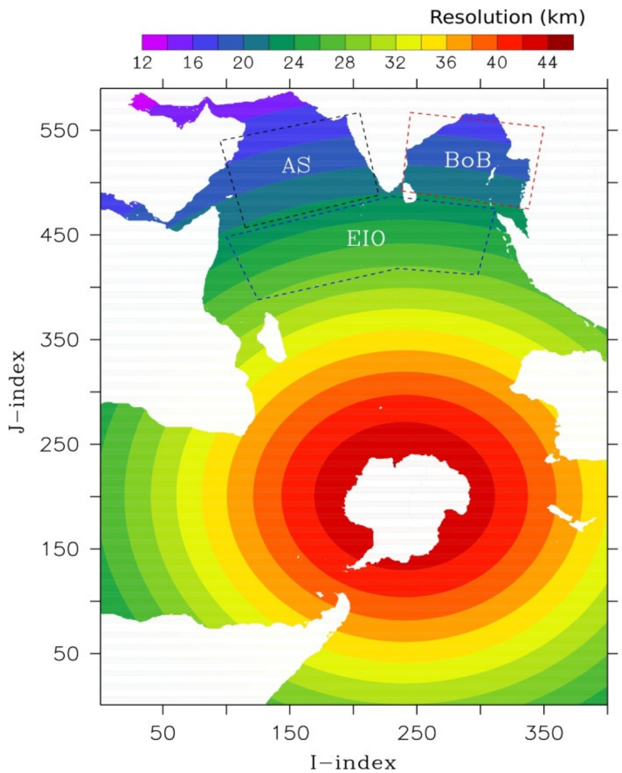
HYCOM is a hybrid coordinate model based on MICOM and is able to interchange between different coordinate schemes. It is a primitive equation general circulation model. The vertical coordinates remain isopycnic in the open stratified ocean. In weakly stratified upper ocean they smoothly transfer to z-coordinates and in the shallow coastal waters transfers to σ-coordinates.



Model domain with resolution in km.

HYCOM – INDIA

Grid distance – 14 to 42 km (14-26 km in the northern parts).
30 vertical hybrid layers.
Vertical mixing scheme – KPP.
Topography interpolated from GEBCO.
Initialised using GDEM climatology.
Relaxation to climatology at the open boundaries.
Surface relaxation – 50 days
Spun up for 8 years using climatology and thereafter a 13-year model run was carried out using synoptic forcing from ERA 40 reanalysis.
Indonesian Through-Flow (ITF) - 10Sv

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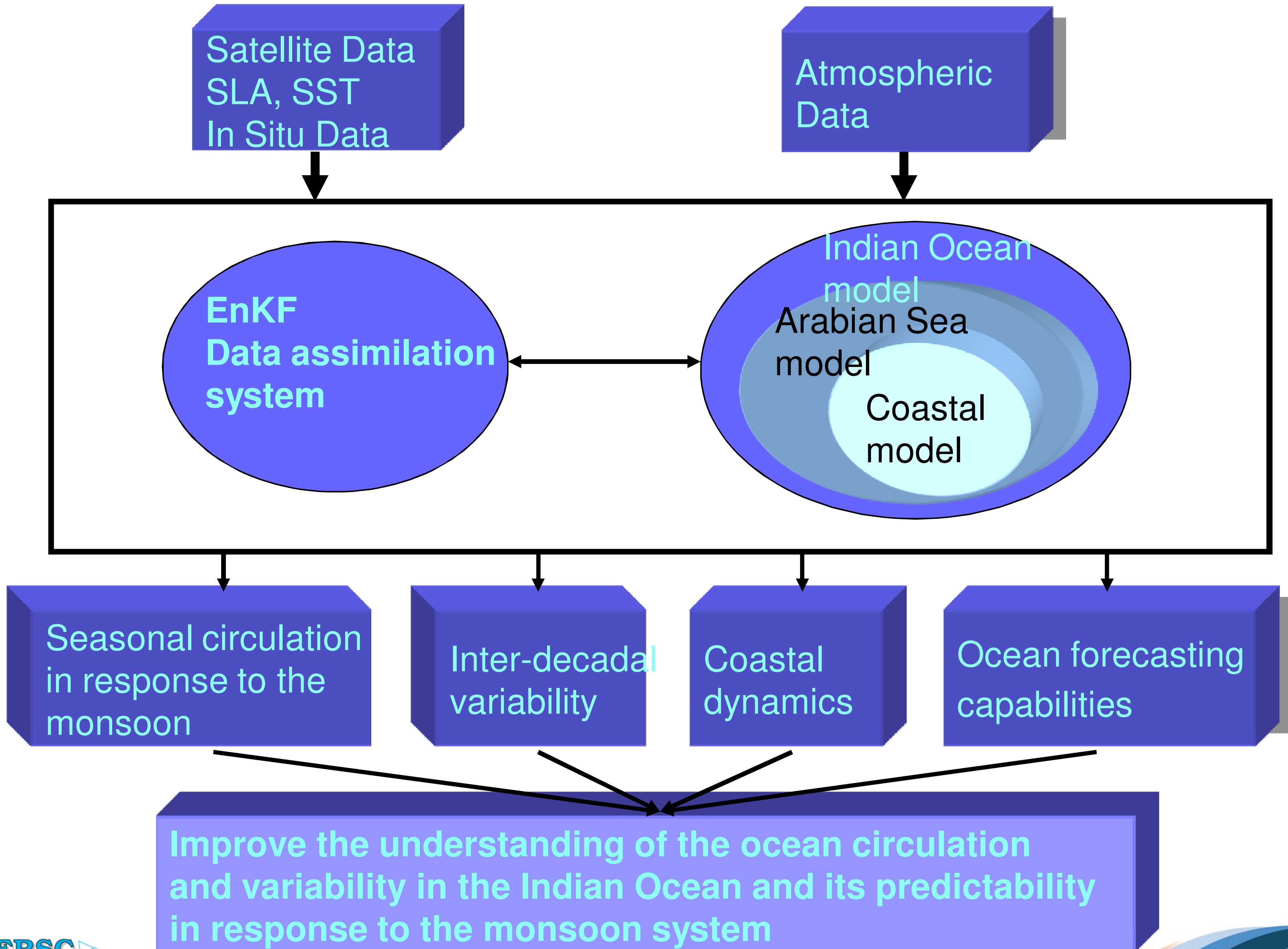

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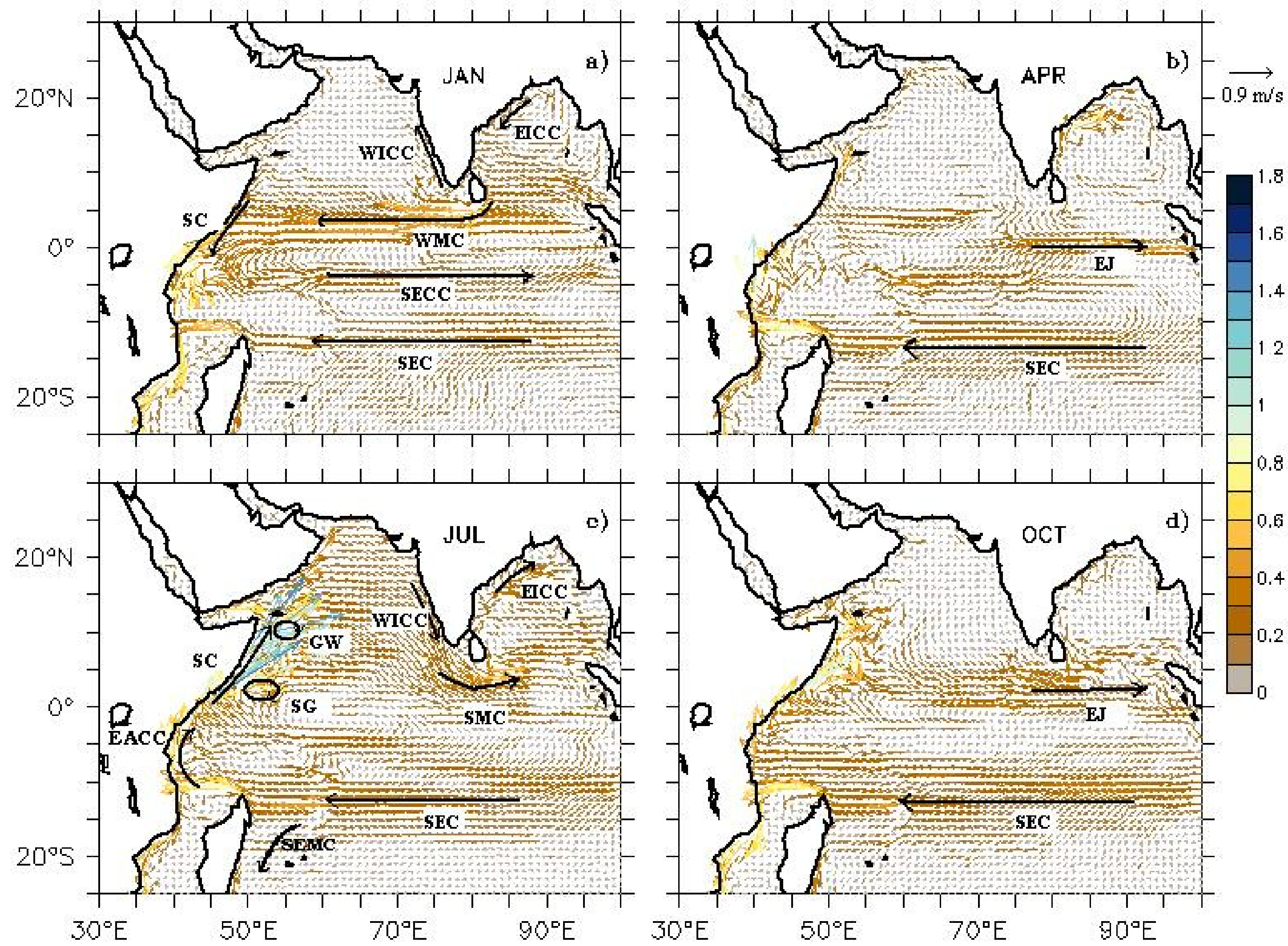
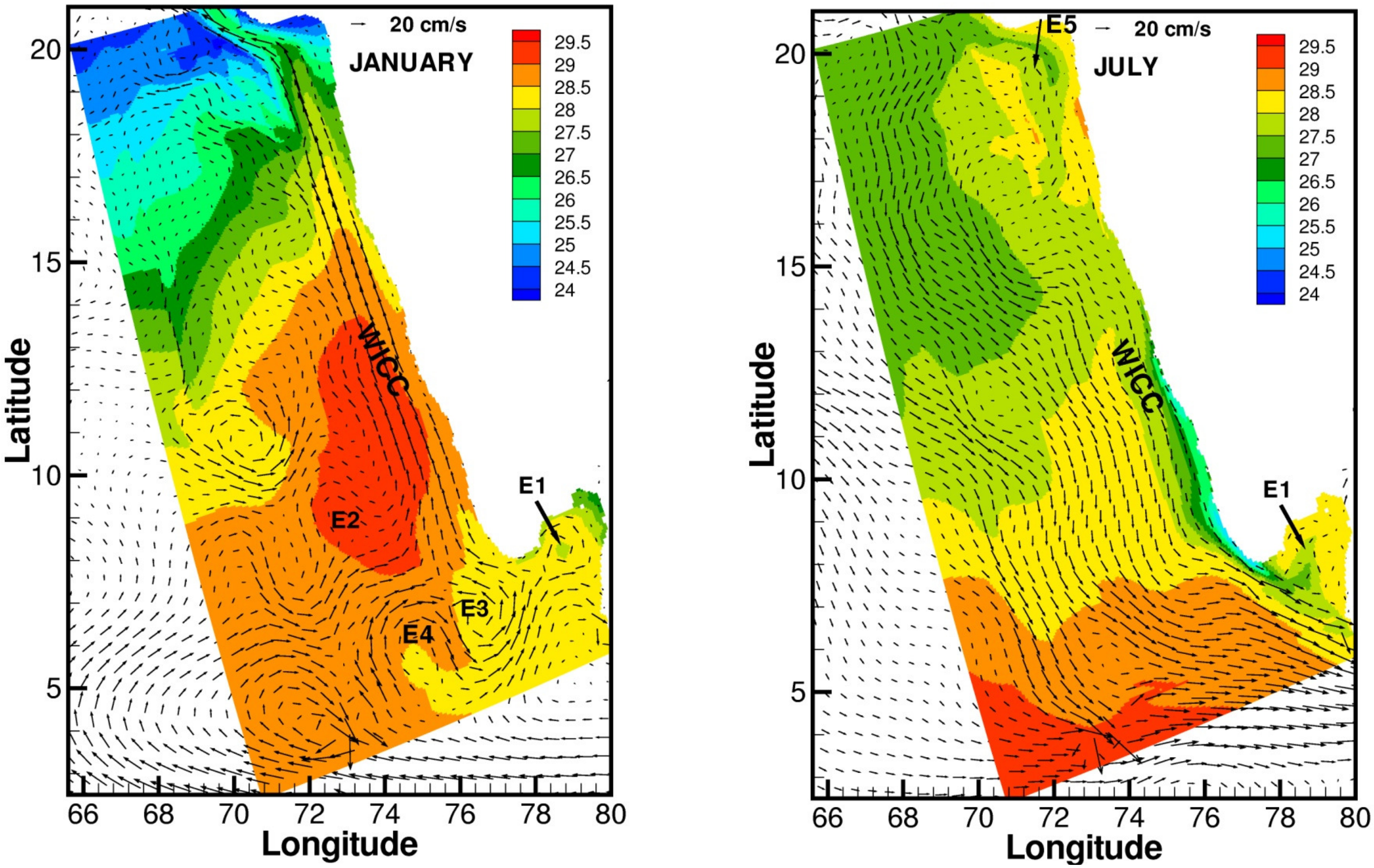


Surface currents simulated by HYCOM, average of 8 years, 1994-2001

George, Johannessen et al, 2010

Surface circulation



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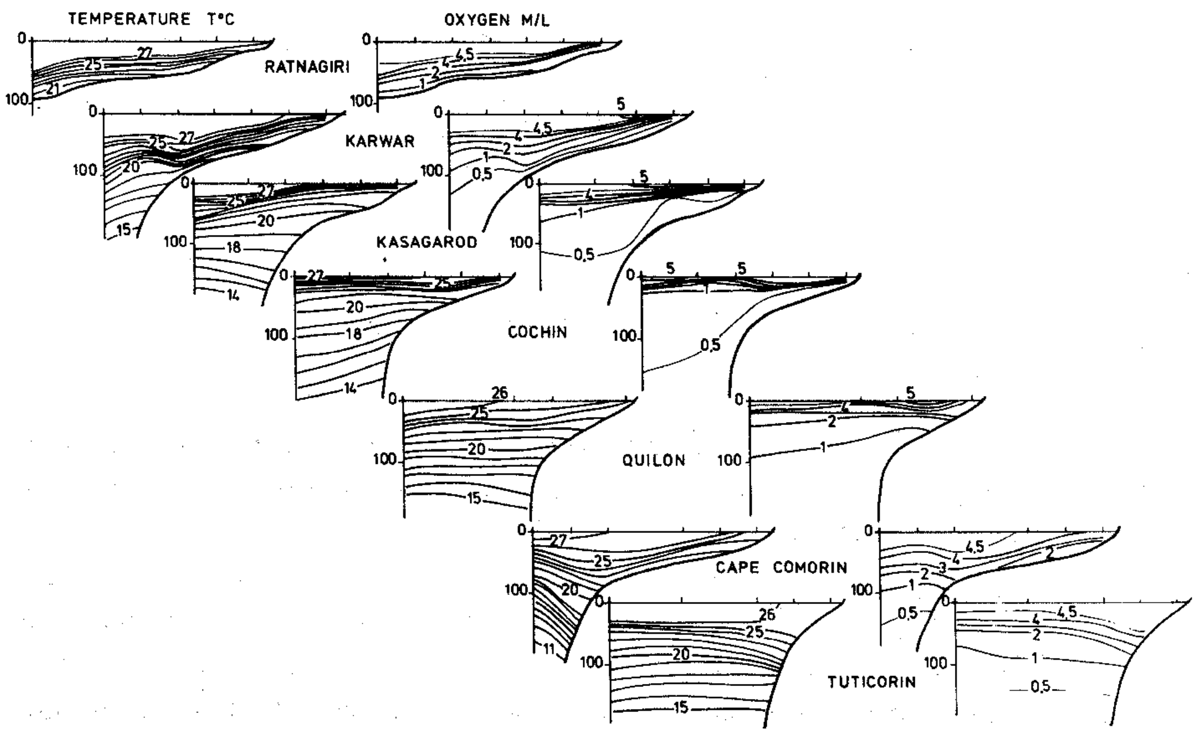
Upwelling along the coast in August 1974



Johannessen et al. (1981)

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Based on the following papers

- Johannessen, O.M., G. Subbaraju and J. Blindheim (1981) Seasonal variations of the oceanographic conditions off the southwest coast of India during 1971-1975, *Fiskfir. Skr. Ser. Havunders.*, **18**, pp. 247-261
- Haugen, V.E., O.M. Johannessen and G. Evensen (2002) Indian Ocean: Validation of the Miami Isopycnic Coordinate Ocean Model and ENSO events during 1958-1998, *J. Geophys. Res.*, **107**(C5), 2000JC000330
- Haugen, V.E., O.M. Johannessen and G. Evensen (2002) Mesoscale modeling study of the oceanographic conditions off the southwest coast of India, *Proc. Indian Acad. Sci.*, **111**(3), pp. 321-337
- Haugen, V.E. and G. Evensen (2002) Assimilation of SLA and SST data into an OGCM for the Indian Ocean, *Ocean Dynamics*, **52**, pp. 133-151

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Sea level and Greenland Ice Sheet

by

Ola M. Johannessen

NANSEN Environmental and Remote Sensing Center

WCRP CORDEX South Asia Planning Meeting

25-26 February 2012

Pune, India

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Rising sea levels will increase coastal erosion.

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Coastal erosion and flooding

Changes in sea level lead to:

- changes in wave pattern and peak water height (storm surges)
- increases in coastal erosion.
- Sea-level rise resulting from global warming will exacerbate natural variability in sea level and local tides.
- In the past century, about 70 per cent of the world's sandy shorelines have retreated. Further erosion is expected as sea level continues to rise.

These changes, combined with changes in the frequency and intensity of severe storms due to climate change, will increase the risk of coastal flooding and erosion.

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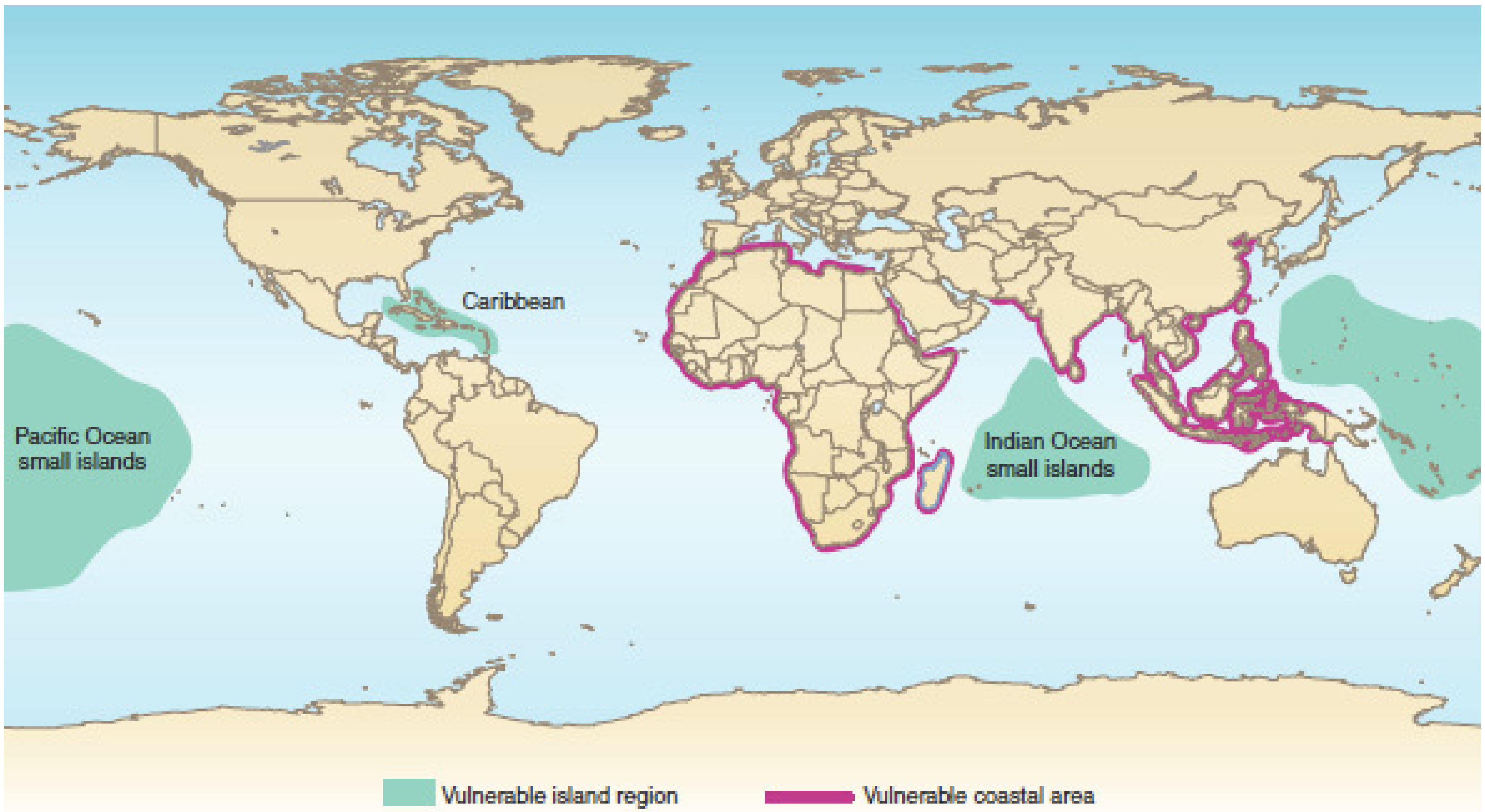
Several regions are vulnerable to coastal flooding caused by future relative or climate-induced sea-level rise. At highest risk are coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity.



Nicholls and Cazenave 2010

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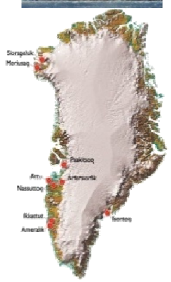
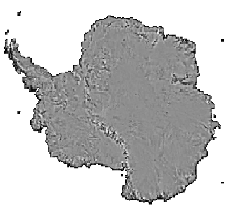
Potential Sea Level Change Contributions

Thermal Expansion –
Potential: ~1 meter; Recent*: 1.2-1.6 mm/yr

Mountain Glaciers –
Potential: 0.5 meters; Recent: ~0.9 mm/yr



Greenland Ice Melt –
Potential: 7 meters; Recent: ~0.75 mm/yr



Antarctic Ice Melt –
Potential: 60 meters; Recent: ~0.4 mm/yr

Land Water Storage –
Potential: < 0.5 meters; Recent: ?

**"Recent" means 1993 - 2006 as measured by satellite altimeters.*

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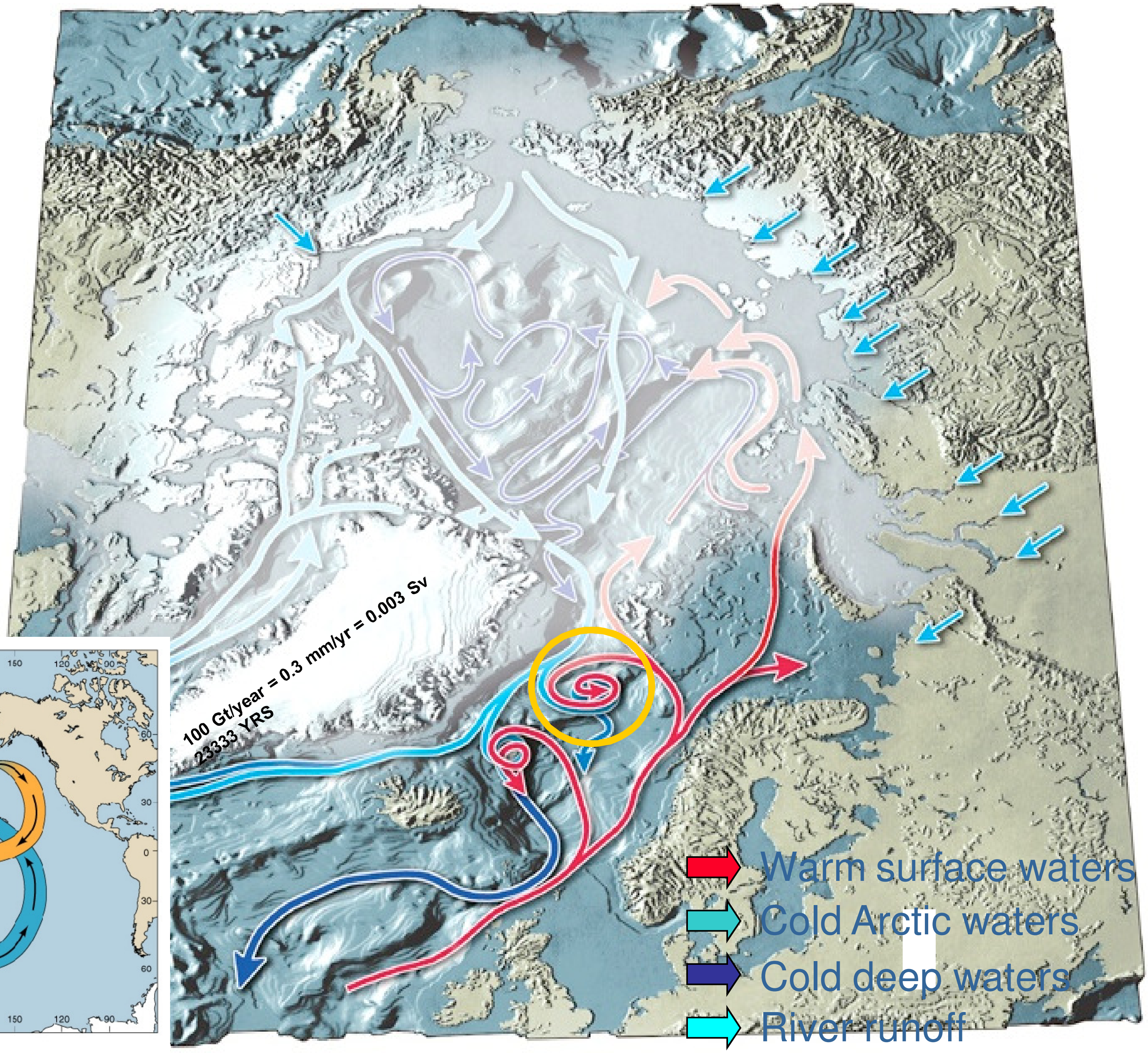
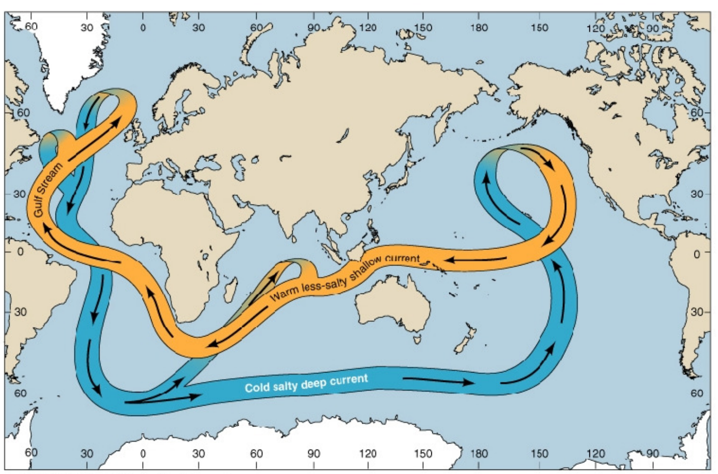
Arctic Climate System

- Warming
- ice/snow melting
- Increase run-off
- Wildcard - Greenland Ice Sheet
- Deep water formation conveyour belt
- Strong natural variablity

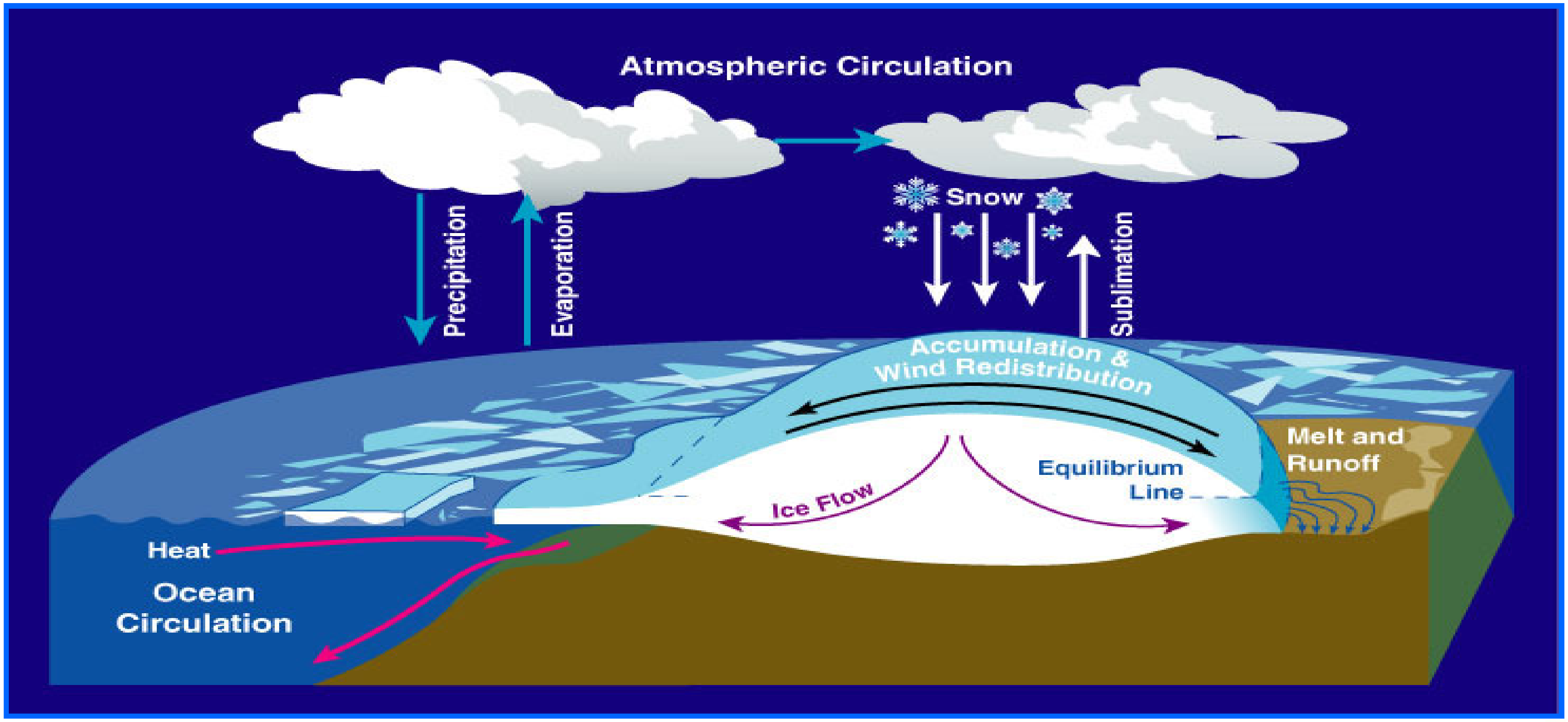




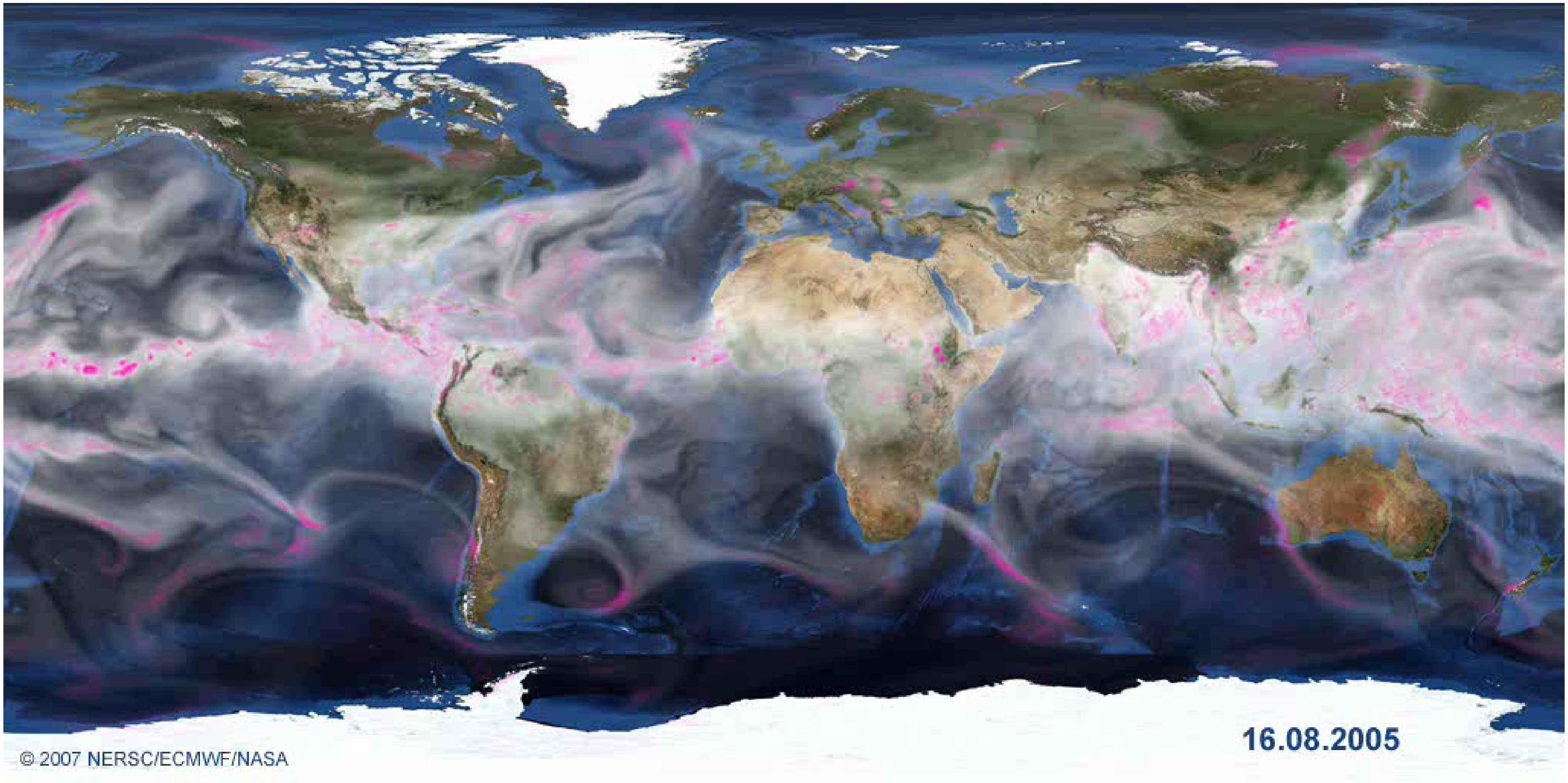
Ice sheet mass balance

Total mass balance = Surface mass balance – Iceberg calving – Bottom melting

Accumulation – Sublimation– Meltwater runoff



Water Vapor Transport



Teleconnection between low and high littitude

Courtesy M. Bentsen, NERSC

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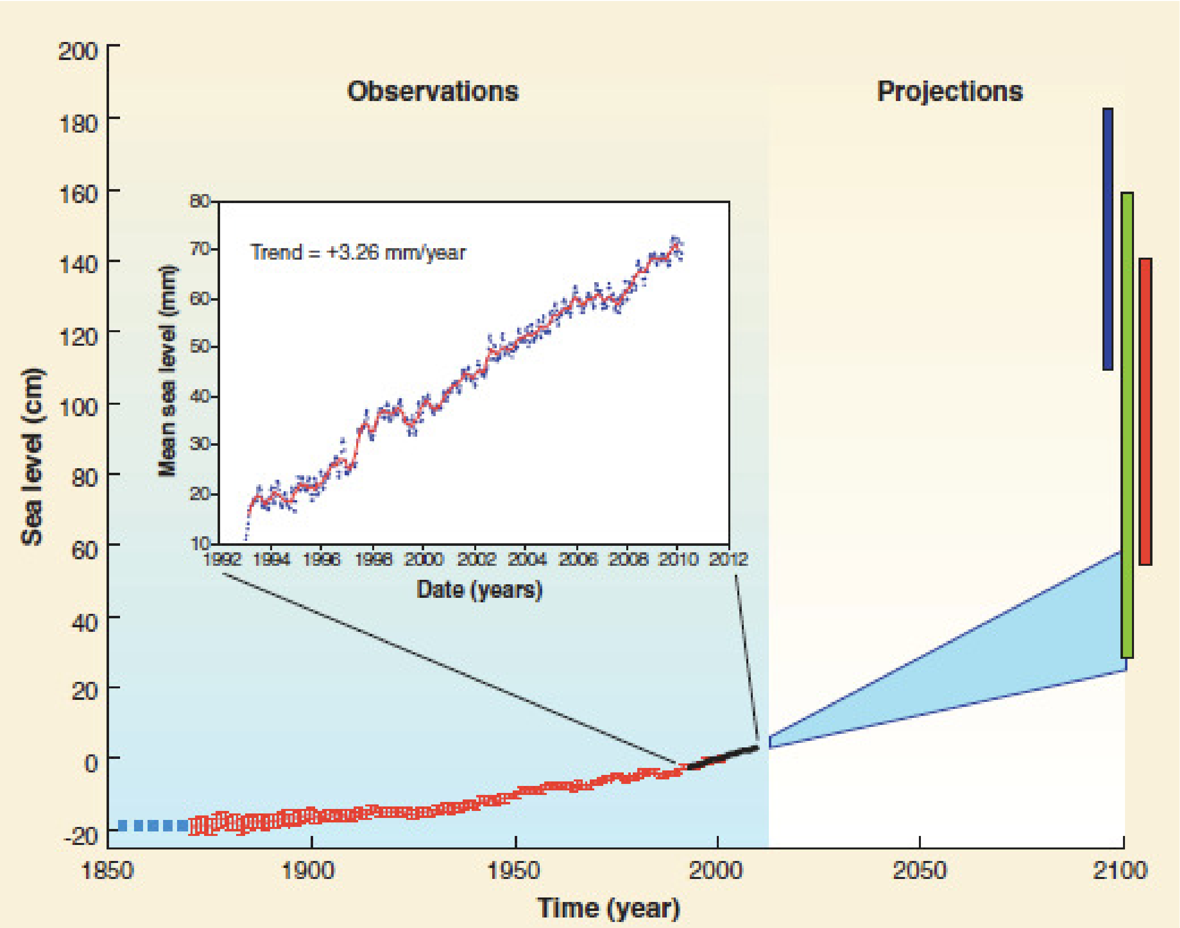
Global mean sea level evolution over the 20th and 21st centuries.



The red curve is based on tide gauge measurements (10). The black curve is the altimetry record (zoomed over the 1993–*2009 time* span) (15). Projections for the the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1FI greenhouse gas emission scenario. Bars are semi-empirical projections

Nicholls and Cazenave 2010

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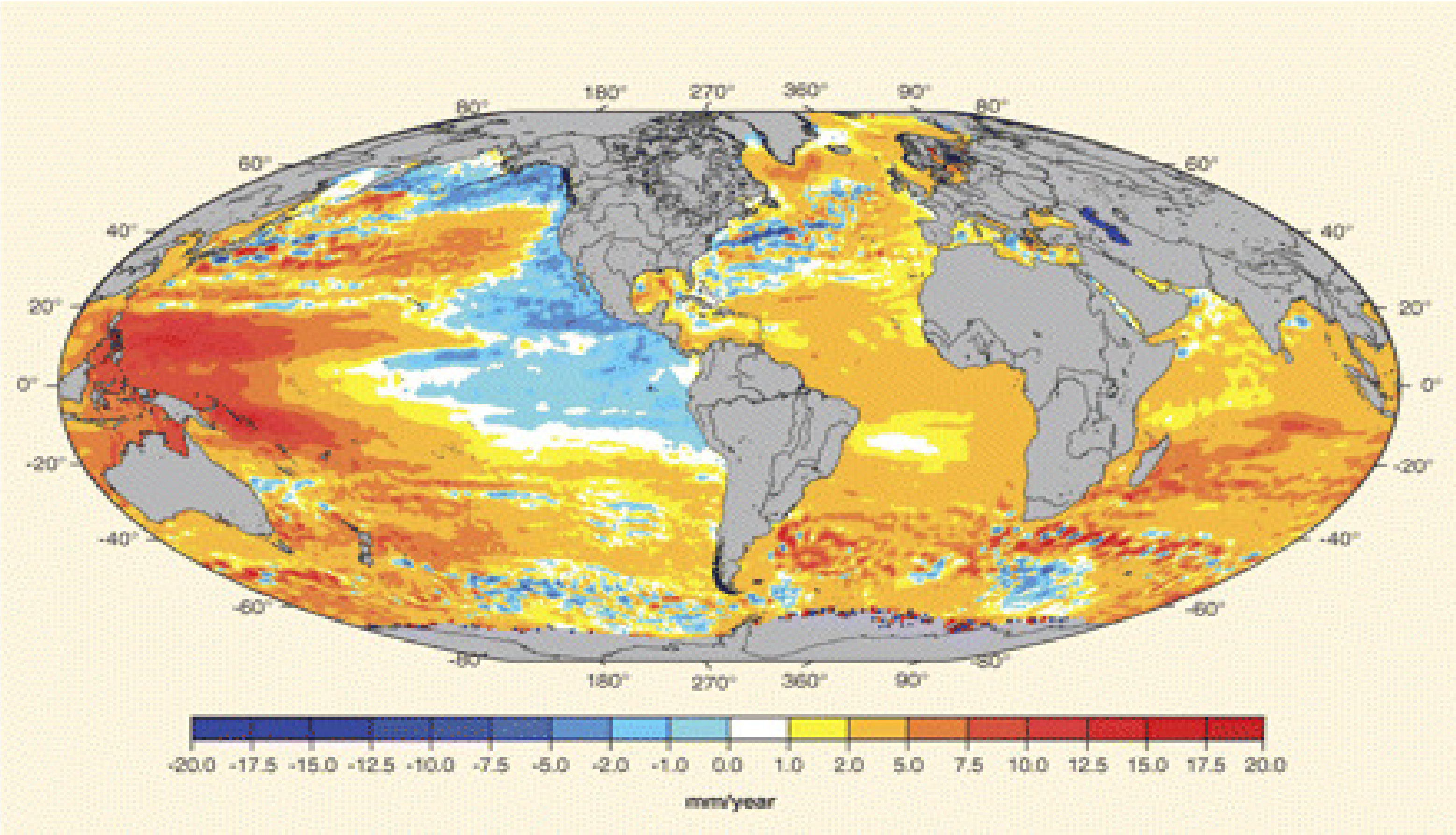
Regional sea-level trends from satellite altimetry (Topex/Poseidon, Jason-1&2, GFO, ERS-1&2, and Envisat missions) for the period October 1992 to July 2009 (48).



Nicholls and Cazenave 2010

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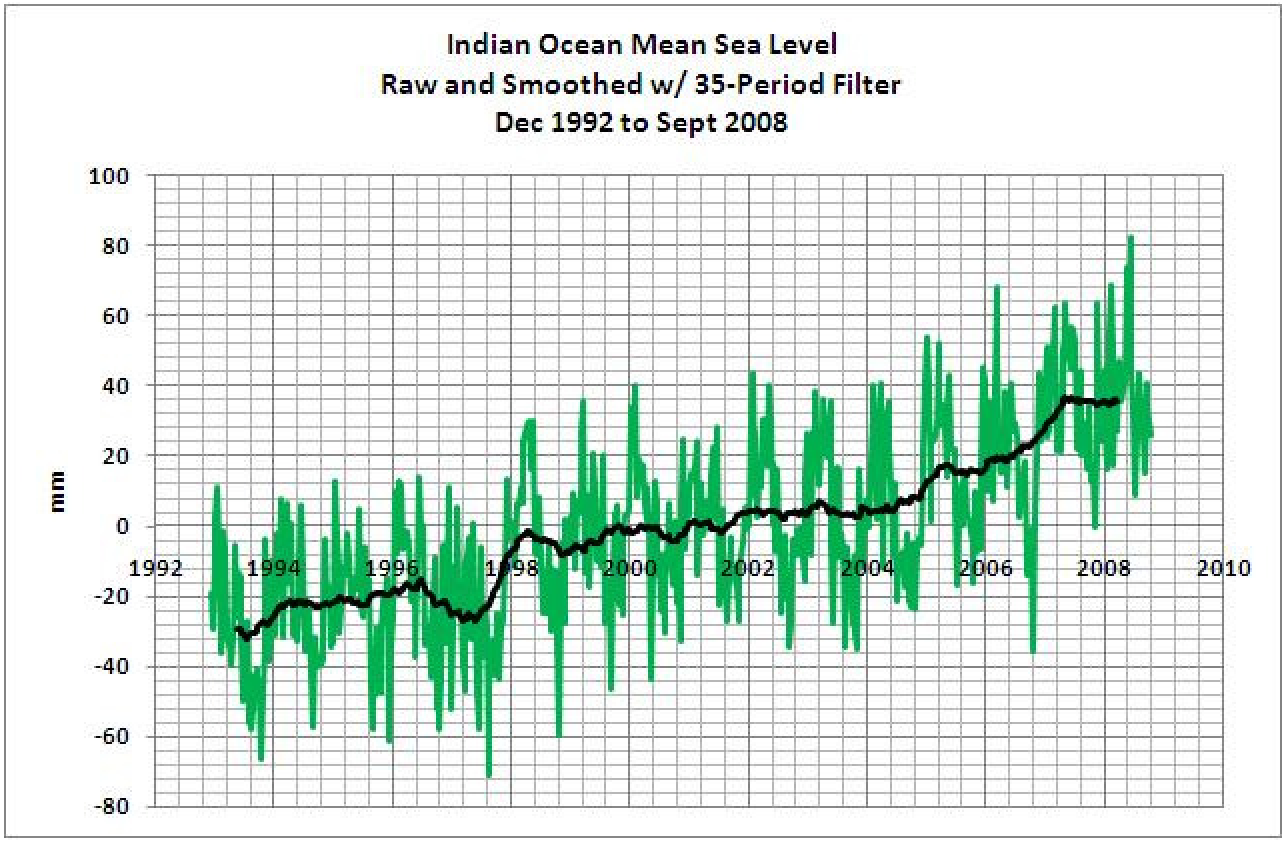

The Indian Ocean Sea Level has not increased since early 2007. Also note the multiple swings in sea level during 1996 and 1997, leading up to the El Nino of 1997/98.

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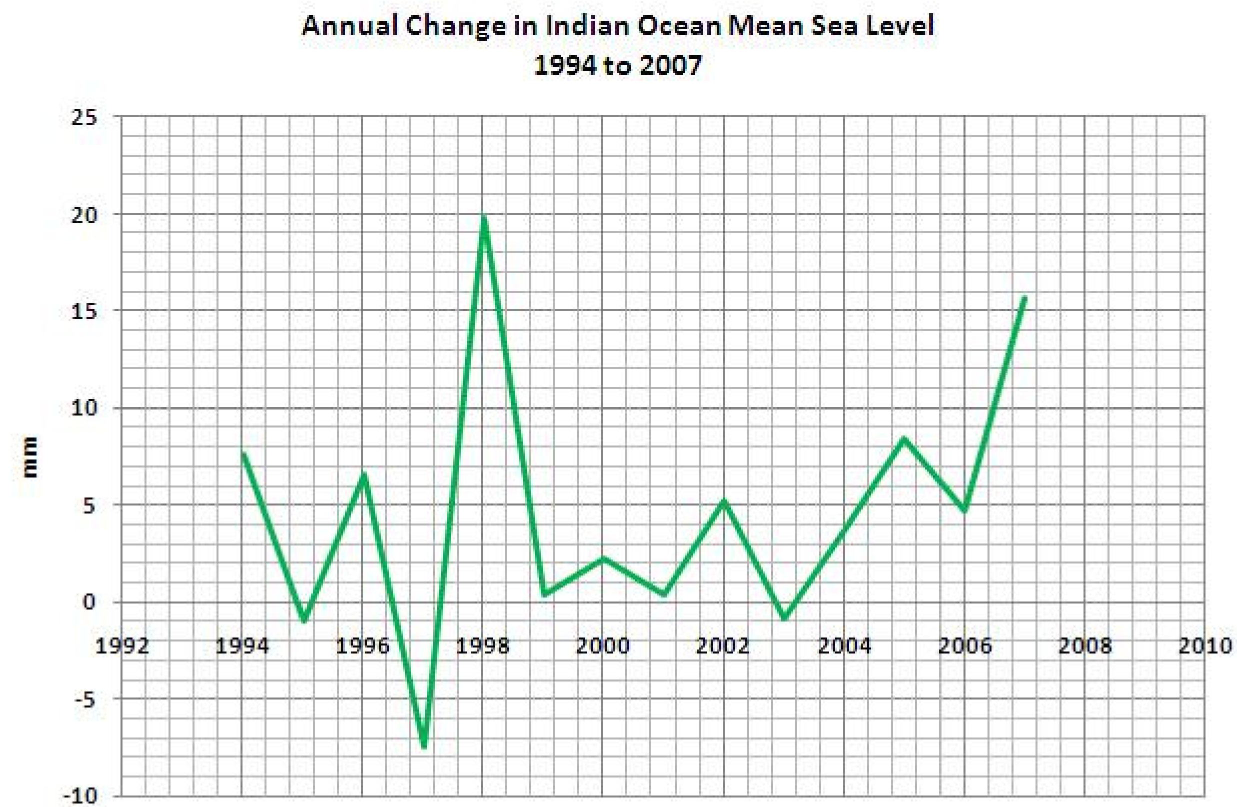
reveals the significant rise in 1998 associated with the 1997/98 El Nino



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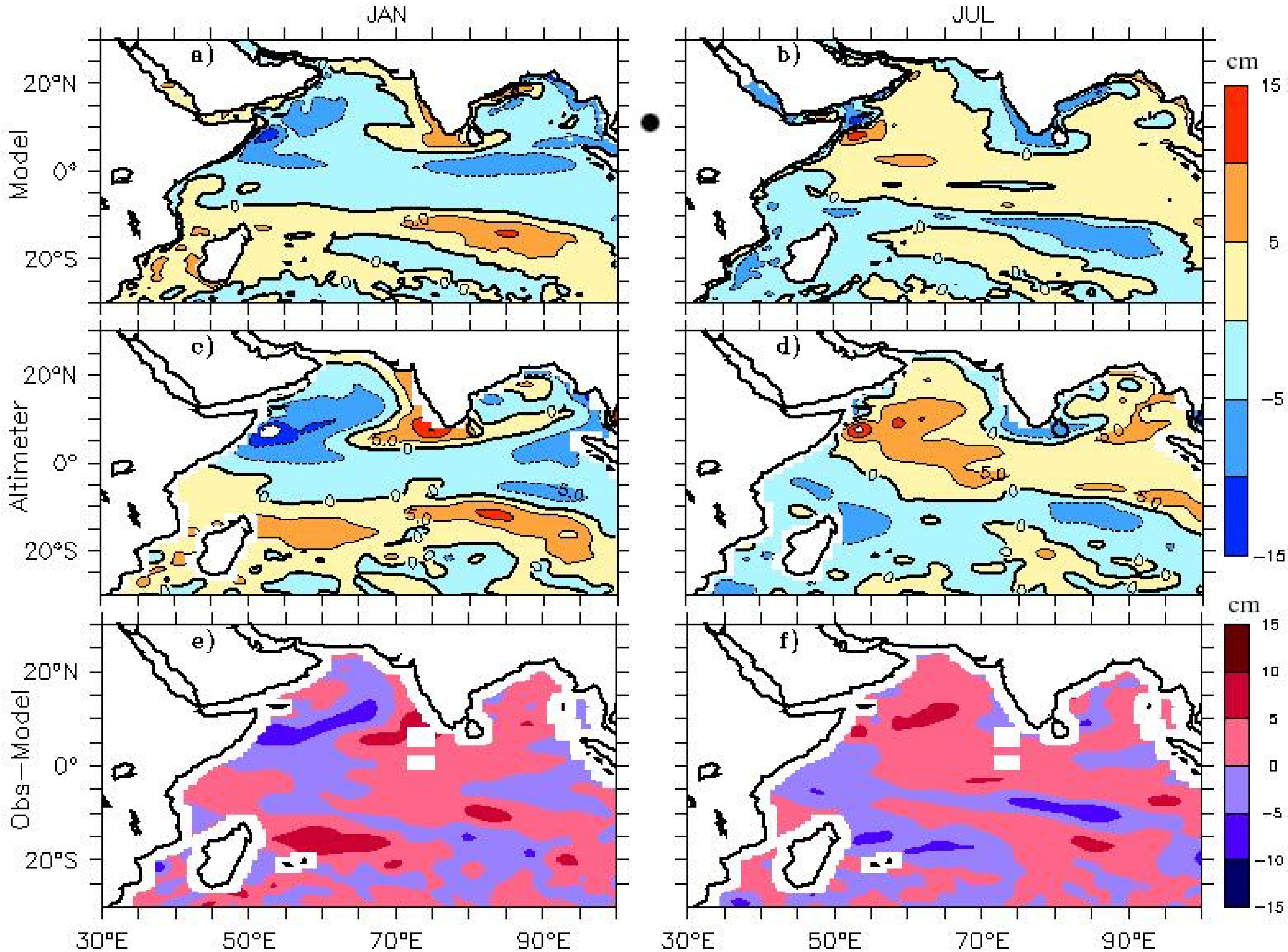

Sea level anomaly (SLA in cm) average of 8 years (1994-2001) from HYCOM (top) and From altimeter measurements(middle). Blue negative anomaly, orange positive. Contour interval 5cm.

George, Johannessen et al, 2010

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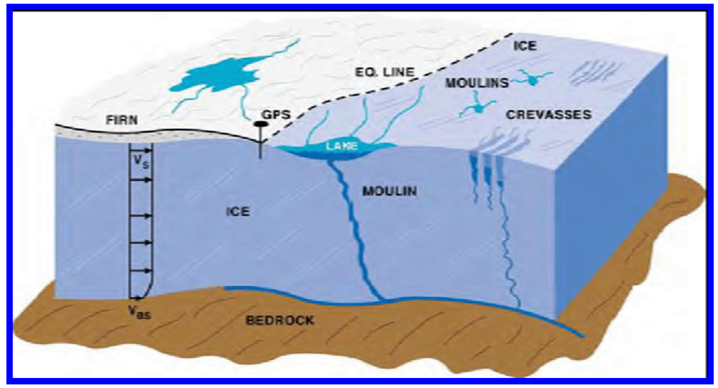
Greenland ice flow: Rapid response to climate change

Surface Melt–Induced Acceleration of Greenland Ice-Sheet Flow

H. Jay Zwally,[1*] Waleed Abdalati,[2] Tom Herring,[3] Kristine Larson,[4] Jack Saba,[5] Konrad Steffen[6]



- Melt water rapidly migrates to the ice sheet base and enhances basal sliding.
- Increasing summer temperatures, more melt water, and greater ice acceleration.

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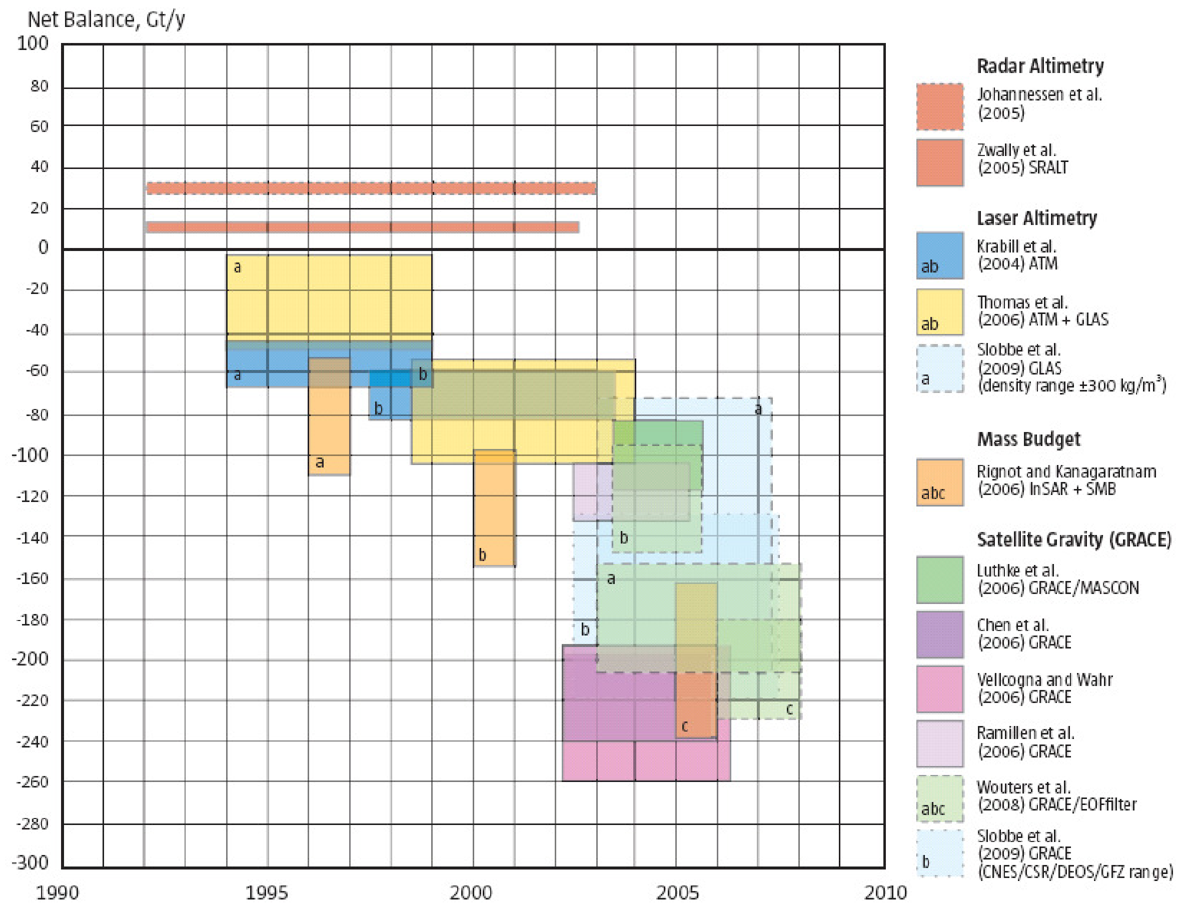
Results from the Recent Large Area Total Balance Measurements



Source: AMAP, 2009. The Greenland Ice Sheet in a Changing Climate: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2009.

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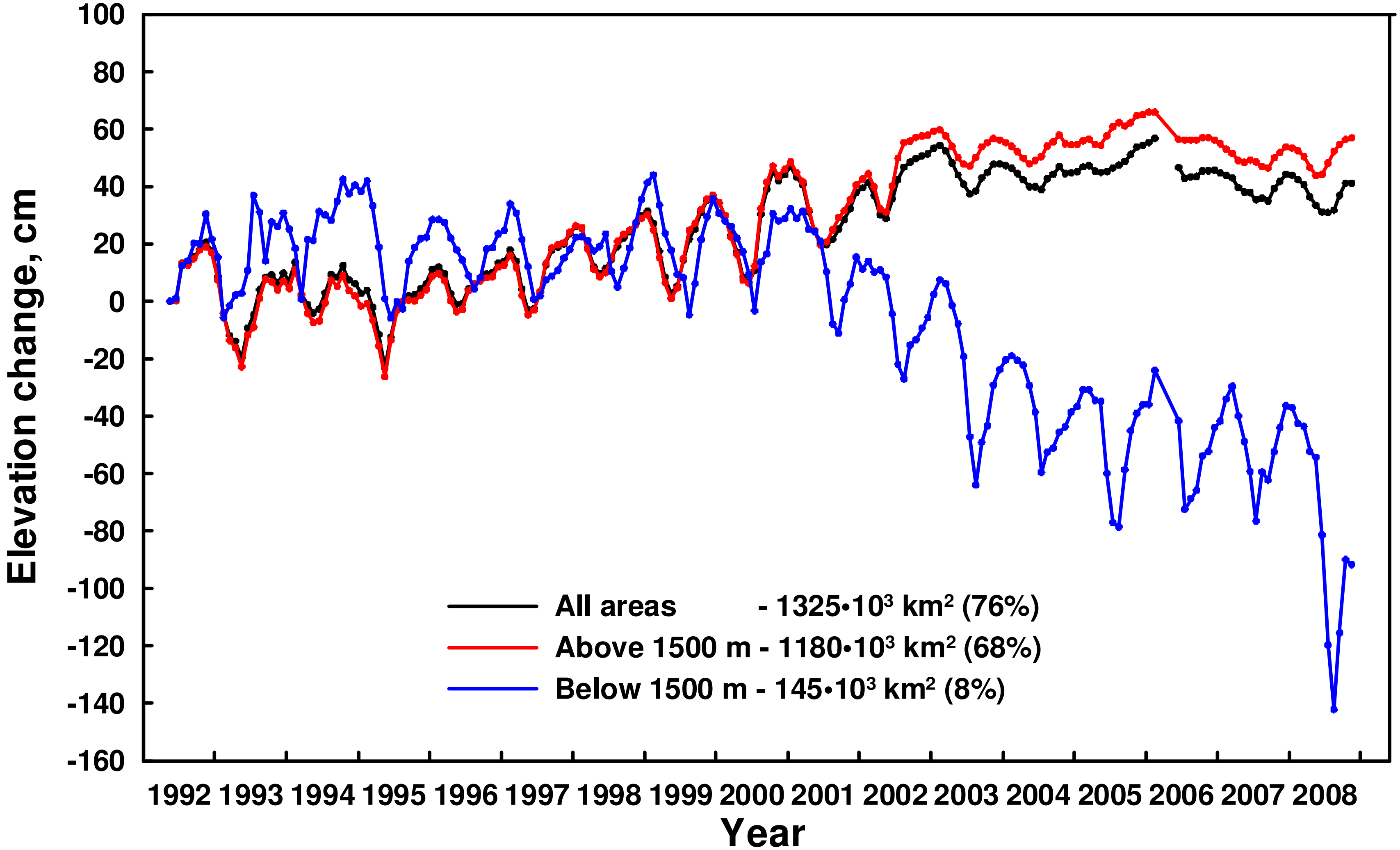
Three-month running mean time series of elevation change



Johannessen et al, Science, 2005 (updated)

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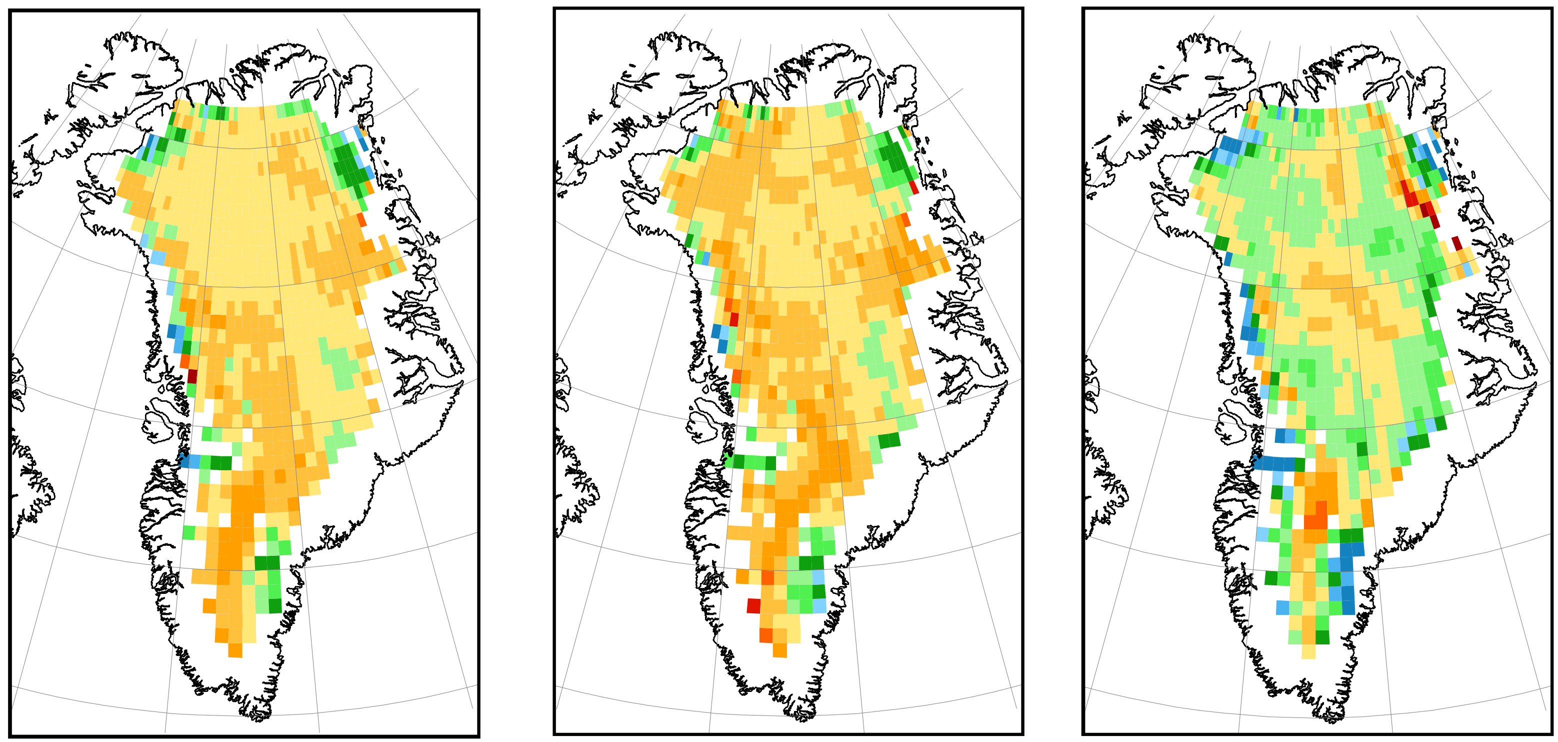
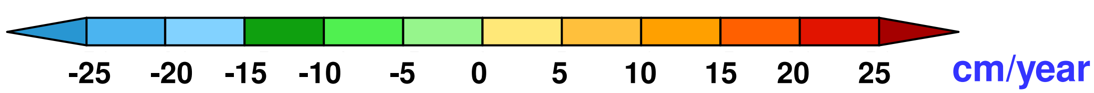
Elevation change rate from merged ERS-1, ERS-2 and Envisat satellite altimeter measurements

May 1992 to November 2008 | **May 1992 to May 2003** | **November 2002 to November 2008**



3.2 ± 0.2 | **4.2 ± 0.2** | **-1.9 ± 0.3**



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Johannessen et al, Science, 2005 (updated)

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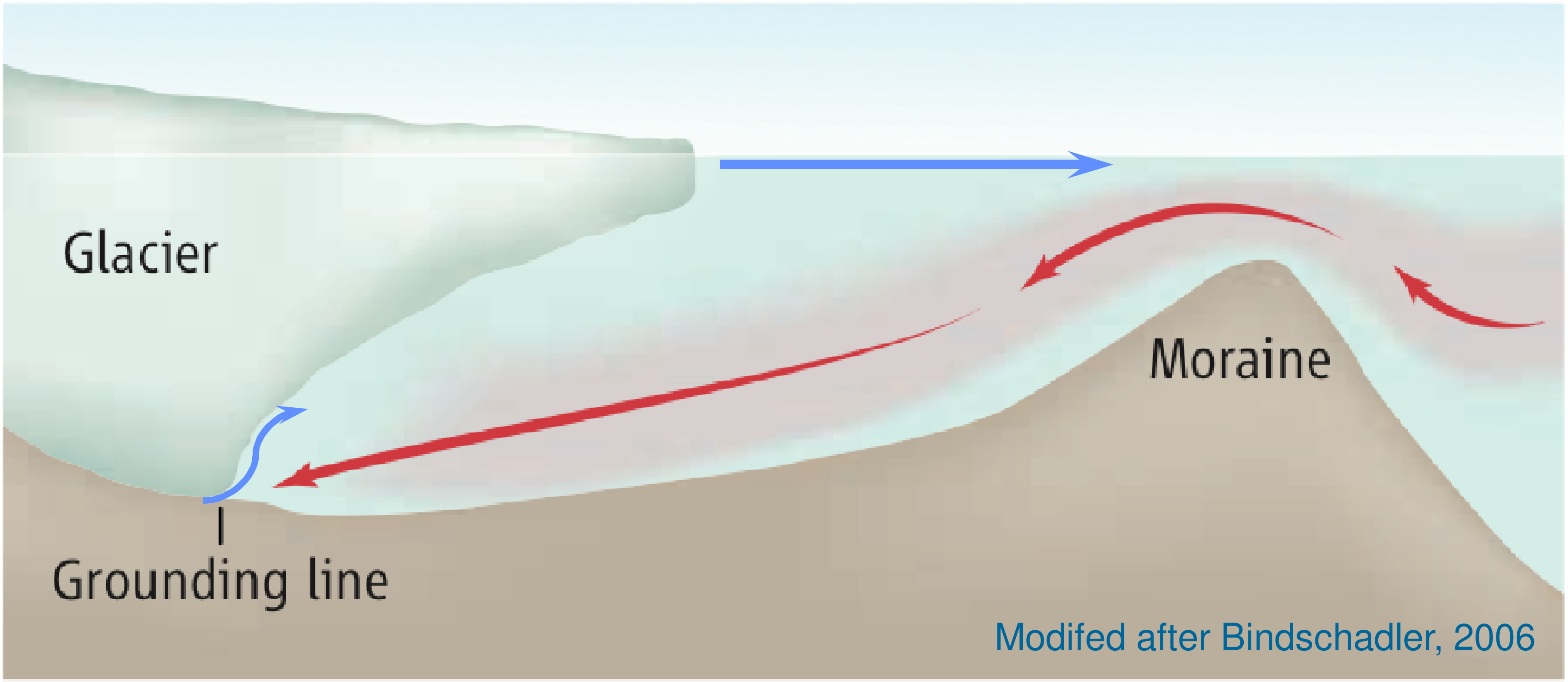

- Cold meltwater comes out of the glacier and at depth, warm seawater comes in and reaches the bottom of the glacier.
- Submarine melting connected with forced convection at the glacier front. (Motyka, 2003)
- Glacier acceleration has been triggered by a combination of atmospheric and oceanic changes

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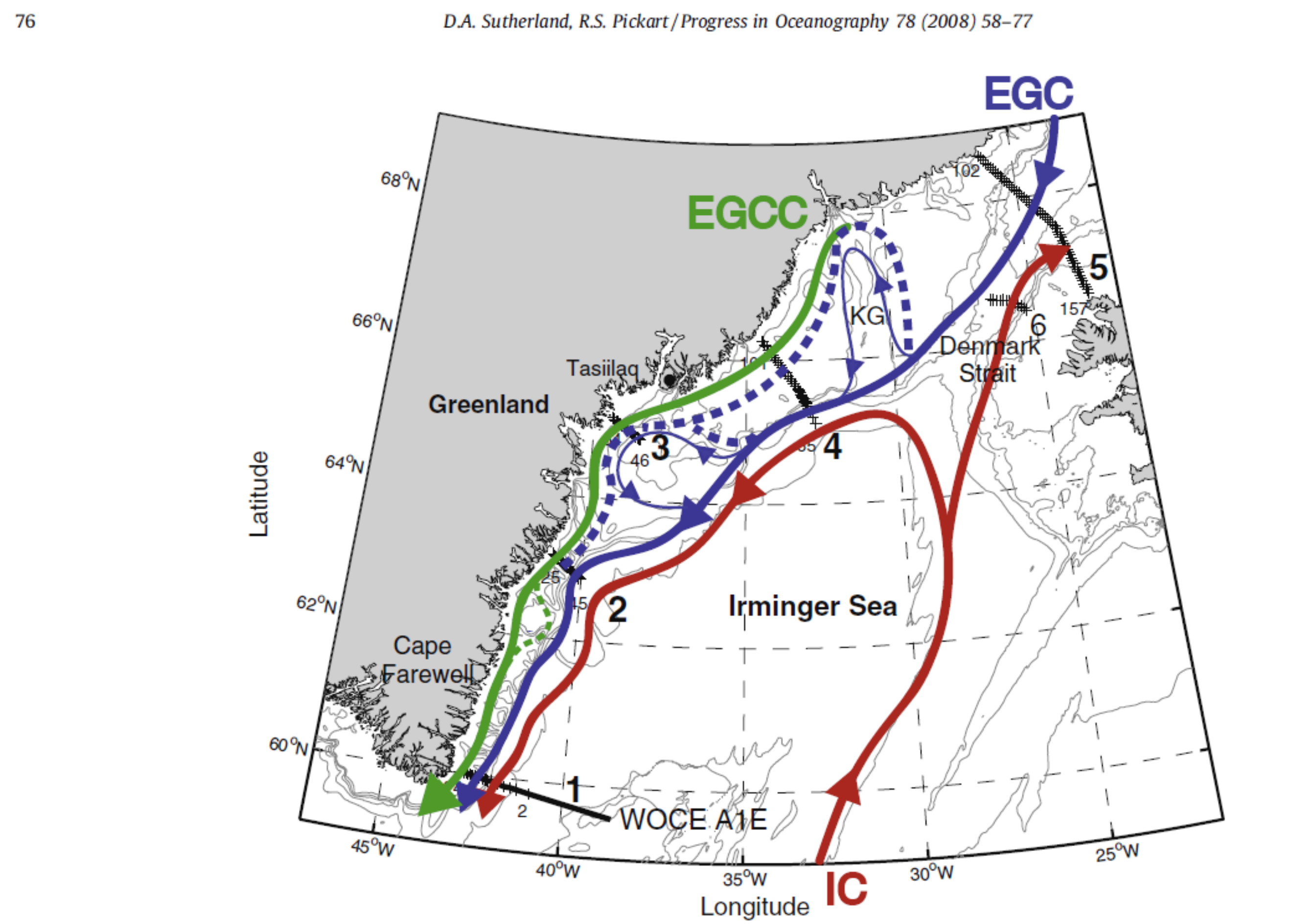
Surface circulation over the southeast Greenland Shelf



EGC -Arctic-origin, low salinity East Greenland Current flows along the shelf break
IC -warm, high-salinity Irminger Current
EGCC -low salinity, high velocity East Greenland Costal Current.
Sutherland et al., 2008

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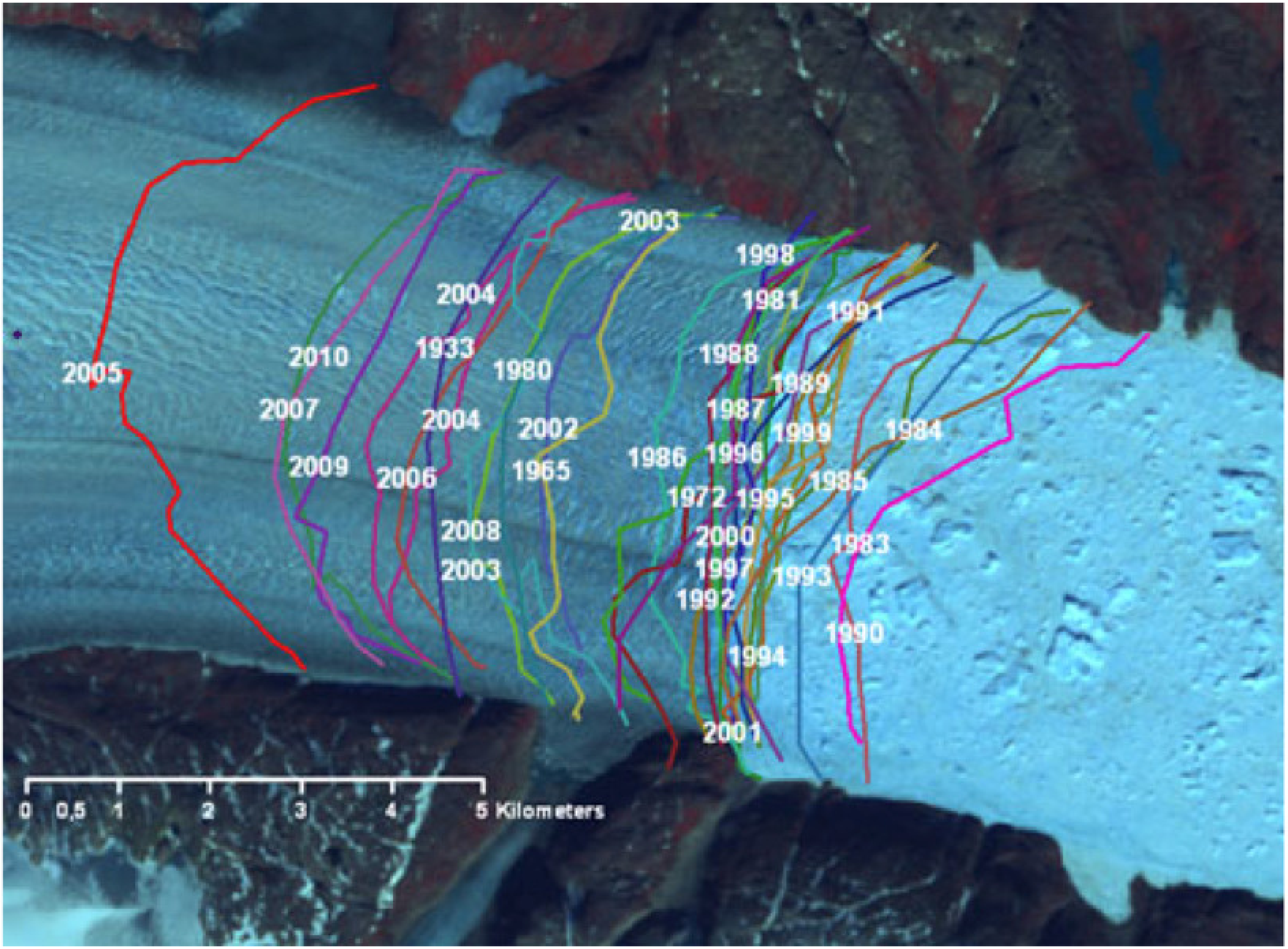

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Helheim glacier ice-front positions each year from 1980–2010, supplemented with a few earlier observations. The ice-front positions are derived from Corona, Landsat, SPOT and ERS 1–2 satellite images

Johannessen et al 2011

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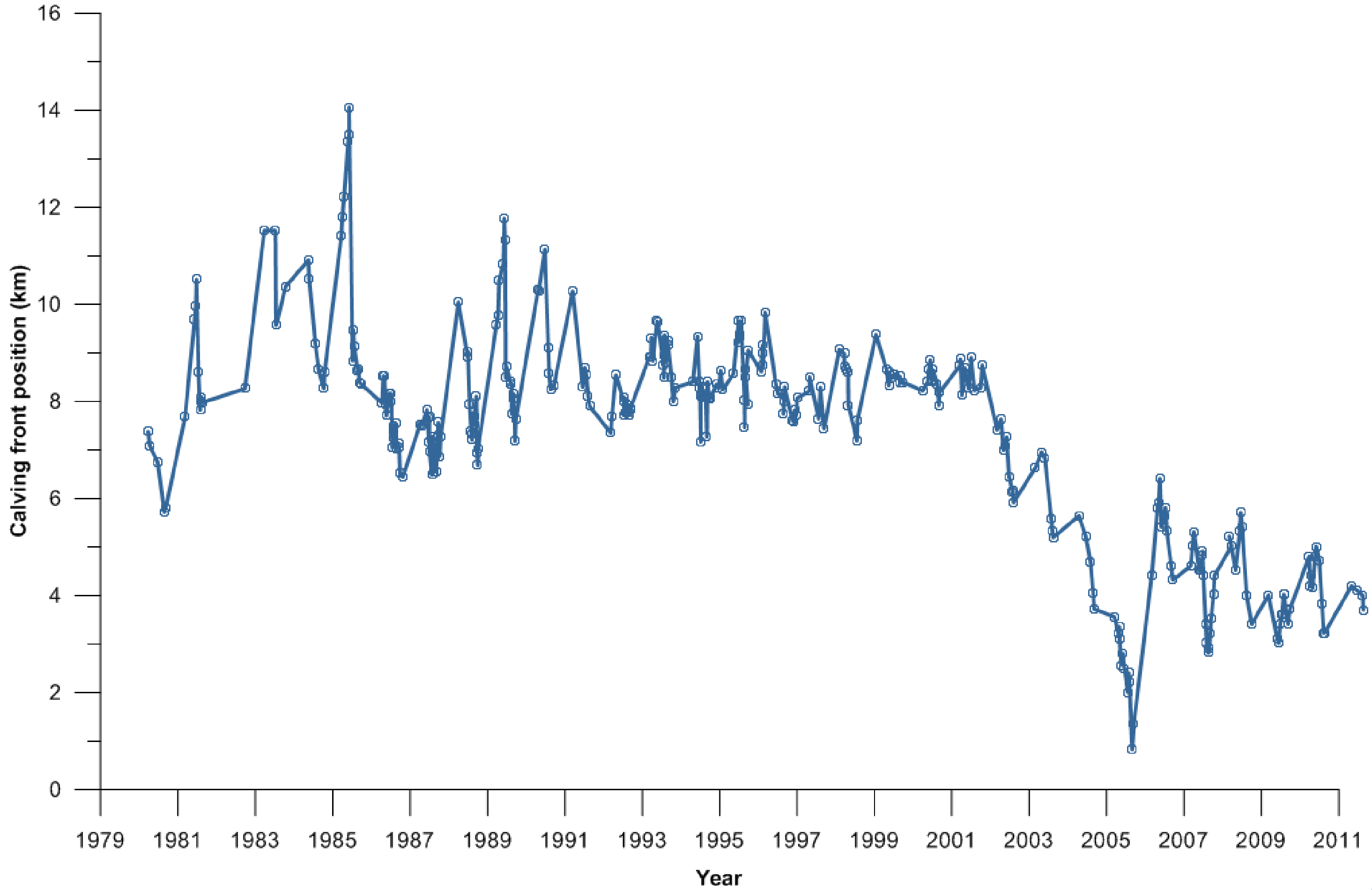
Helheim calving front seasonal and interannual fluctuations,1980–2012



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V. Miles, 2011 (unpublished)

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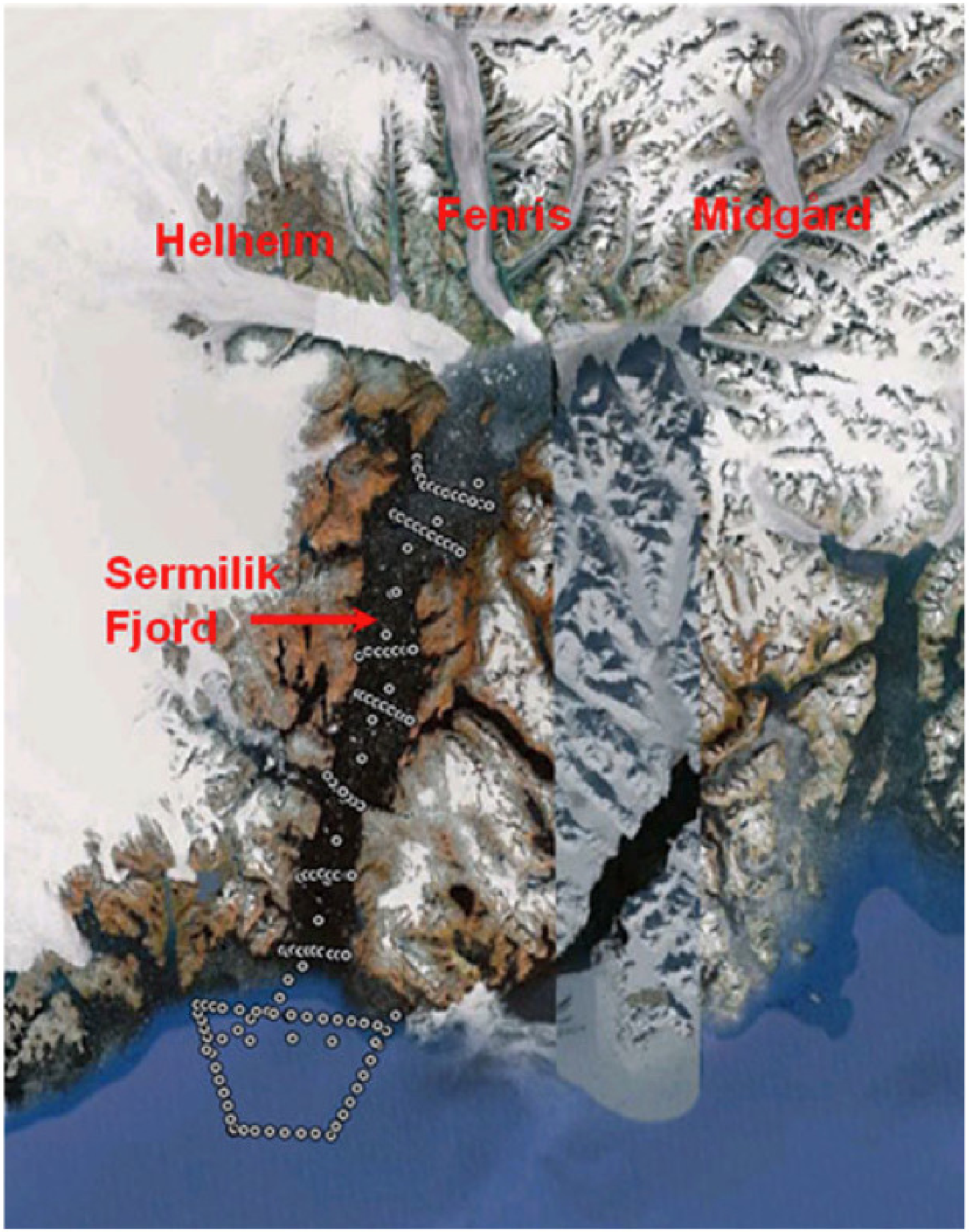

Satellite image showing the outlet glaciers Helheim, Fenris and Midga°rd in the Sermilik Fjord. The CTD station positions in August 2009 are shown as white circles

Johannessen et al 2011

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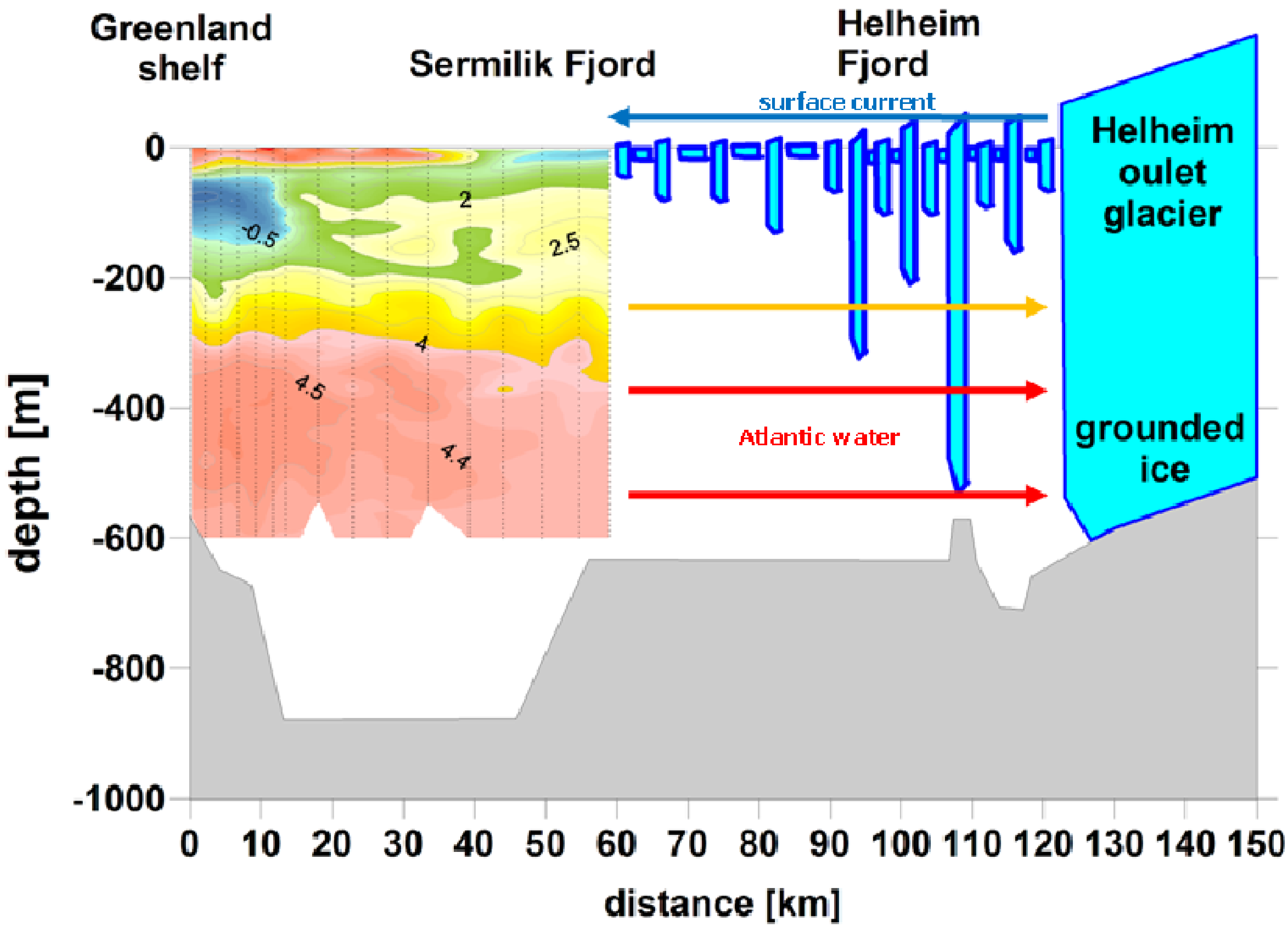

After Johannessen at al., 2011

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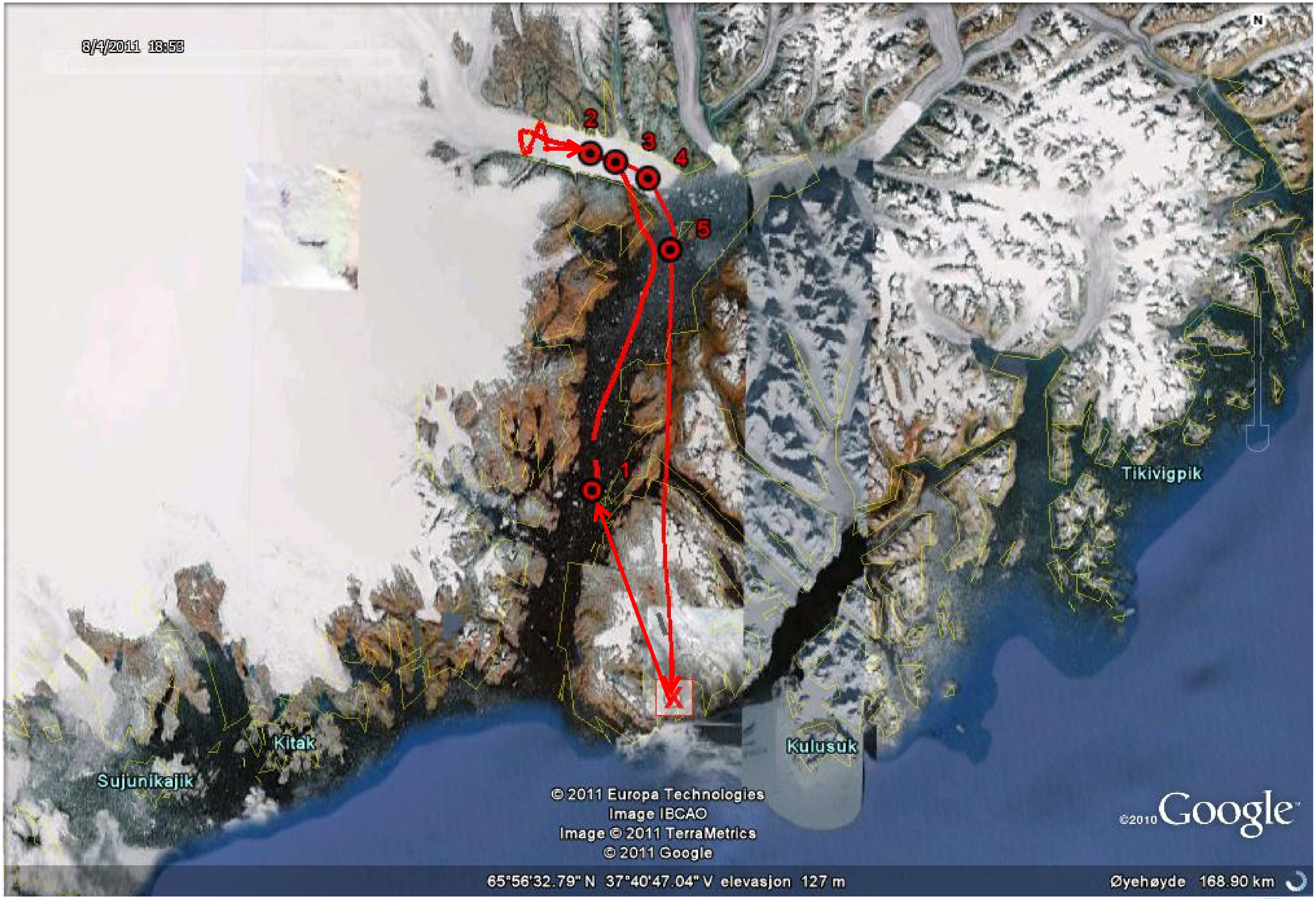

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5 XCTD Drops from helicopter Aug 4th 18:50 – 21:00, 2011

Johannessen et al 2011 unpublished

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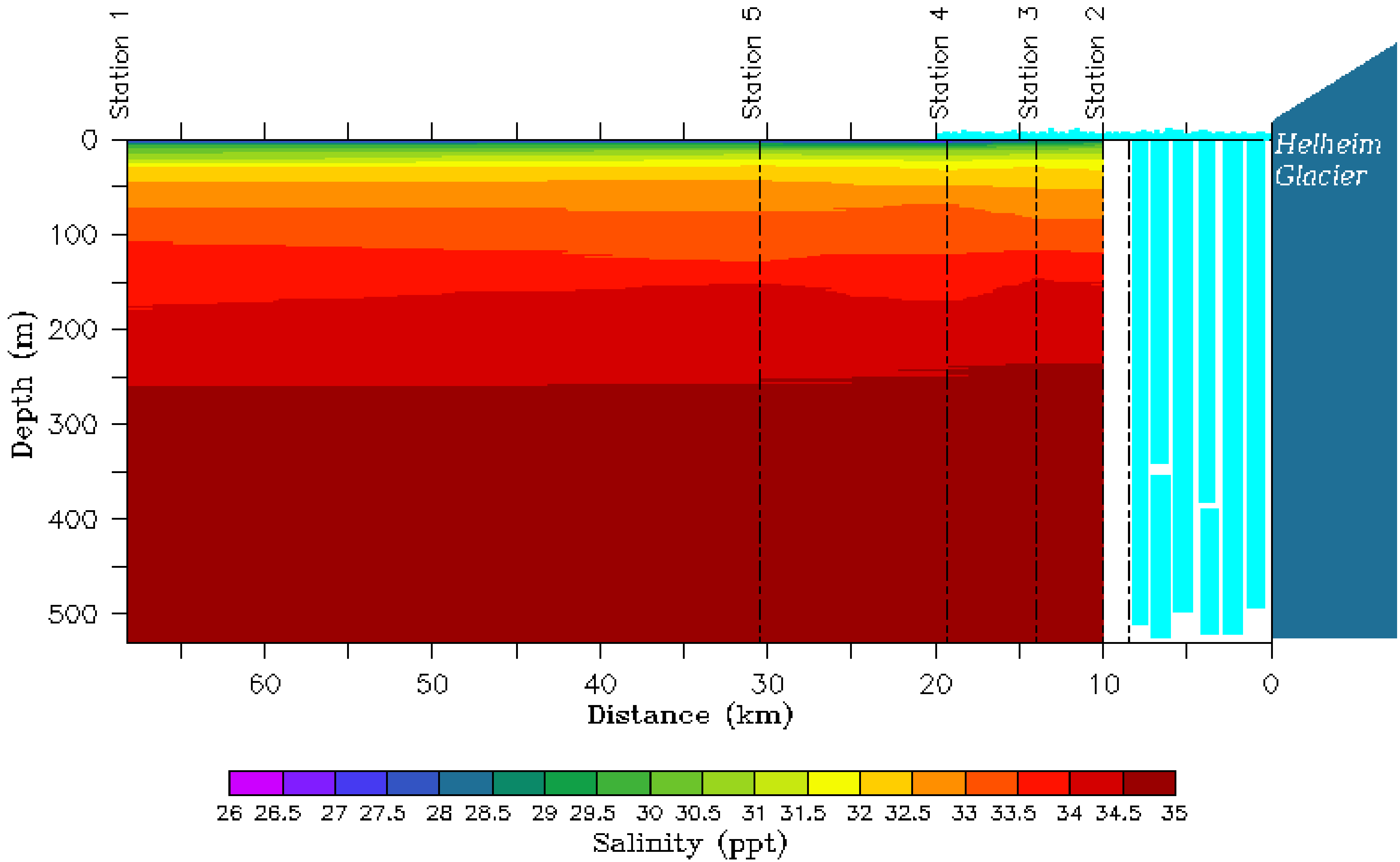

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Johannessen et al 2011 unpubllished

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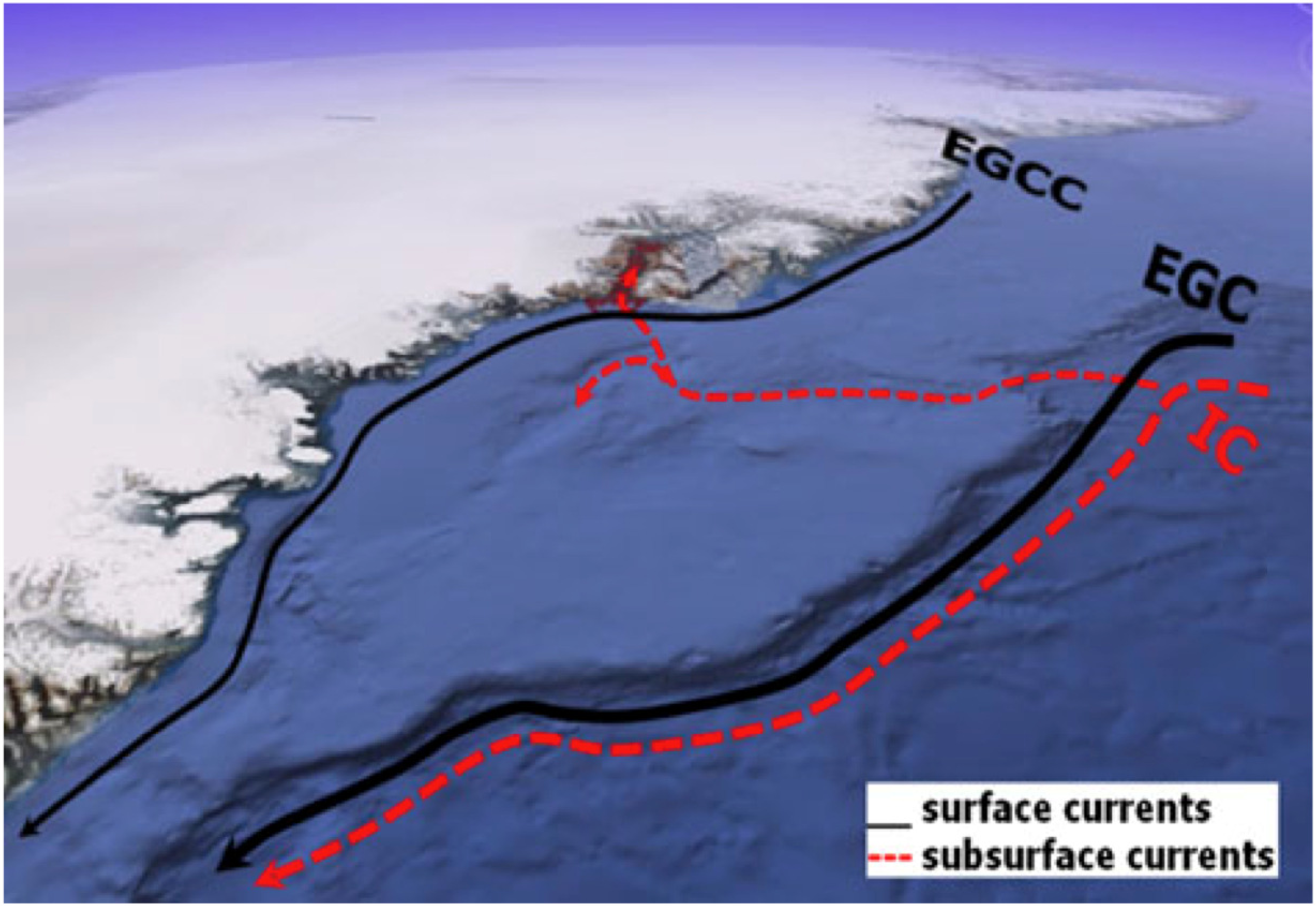

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Schematic of the major warm (red) and cold (black) currents over the Greenland shelf break and shelf including the East Greenland Current (EGC), East Greenland Coastal Current (EGCC) and Irminger Current (IC). The hypothesized trajectory of the Atlantic Water flowing from the shelf break through a canyon into the Sermilik Fjord is also shown

Johannessen et al 2011

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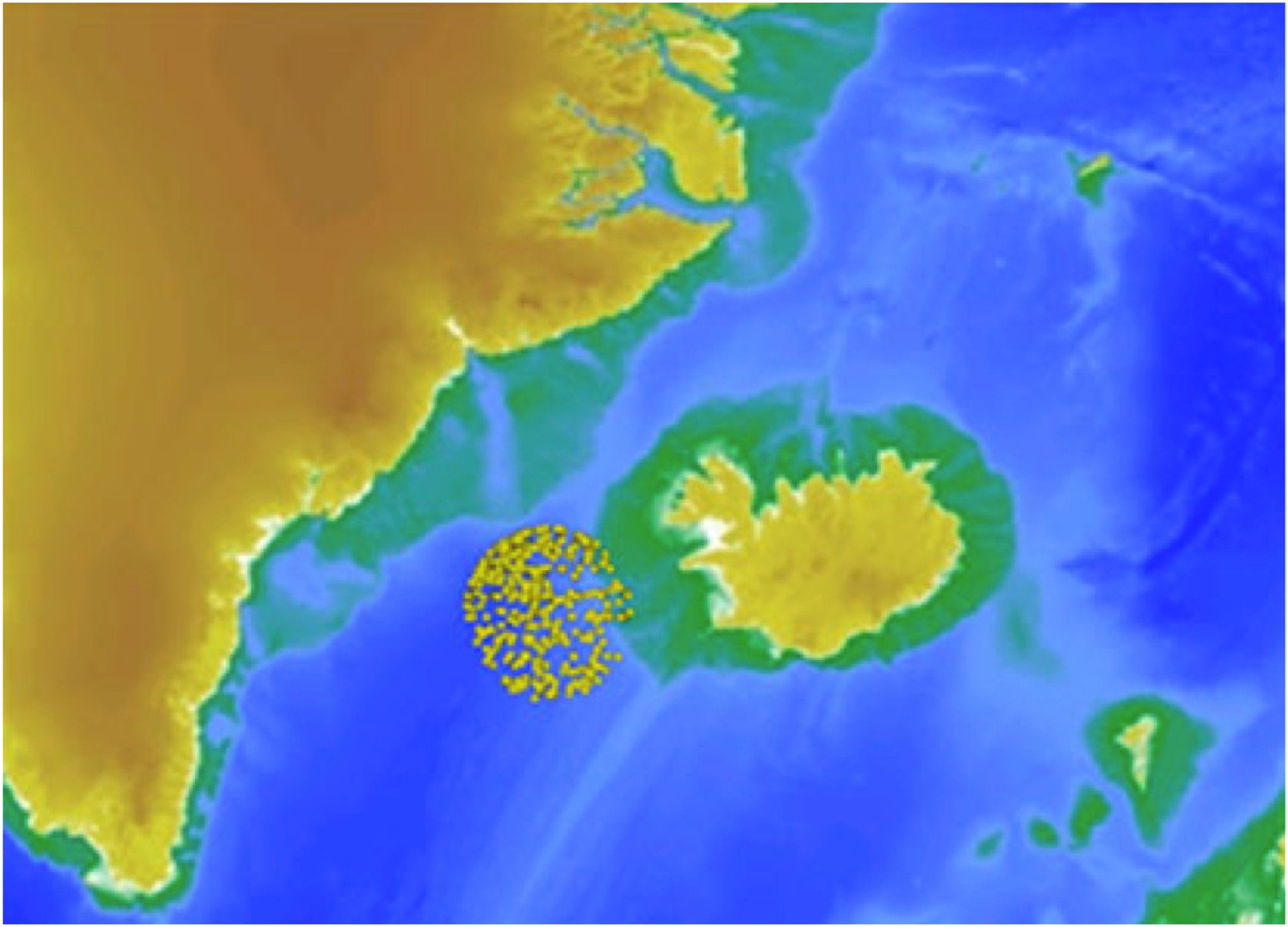

Position of the oceanographic stations 1970–2010 selected to construct water temperature time series for the Irminger

Johannessen et al 2011

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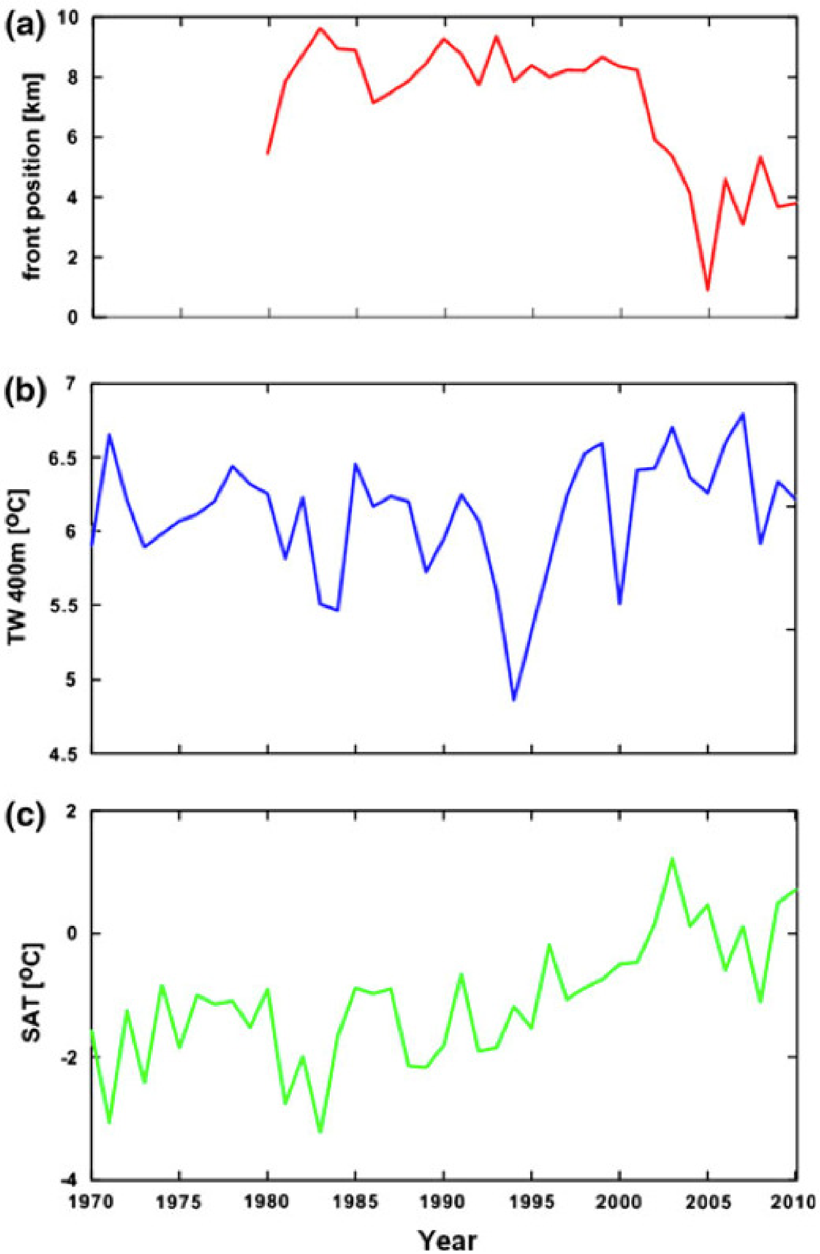

Time series of the Helheim calving front position 1980–2010 in August/September **(a)**, annual water temperature at 400 m depth in the Irminger Sea **(b)** and annual surface air temperature (SAT) 1970–2010 in Tasiilaq, southeast Greenland, 80–90 km east of the Helheim ice-front **(c)**

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Johannessen et al 2011

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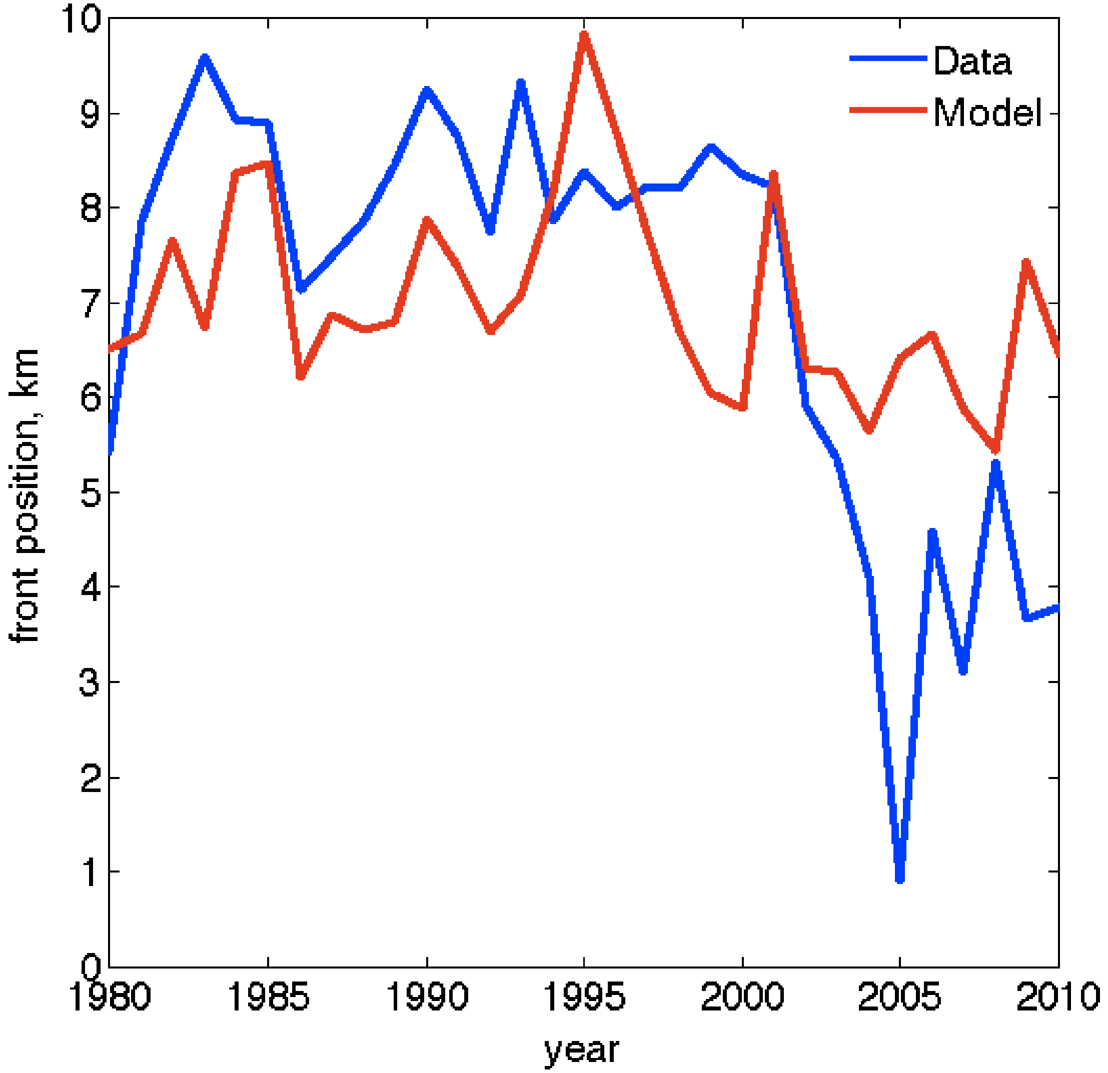
Helheim glacier front position – data and modeled



$$front = 21 - 2.3 \cdot Tw_{-1} \quad R^2 = 22\%$$

Jonannessen et al., 2011

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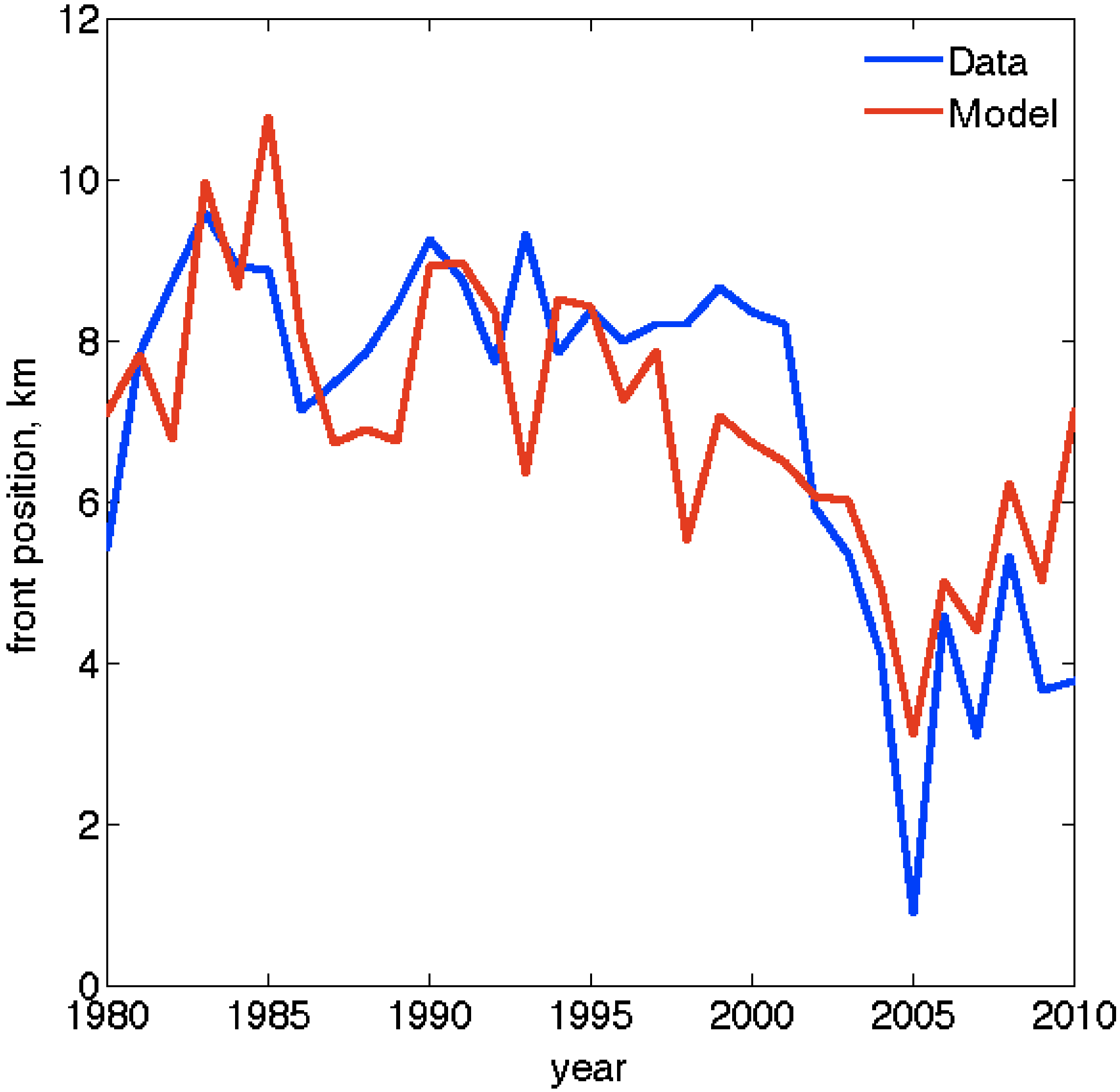
Helheim glacier front position – data and modeled



$$front = 5.2 - 1.7 \cdot SAT_{-2} \quad R^2 = 56\%$$

Jonannessen et al., 2011

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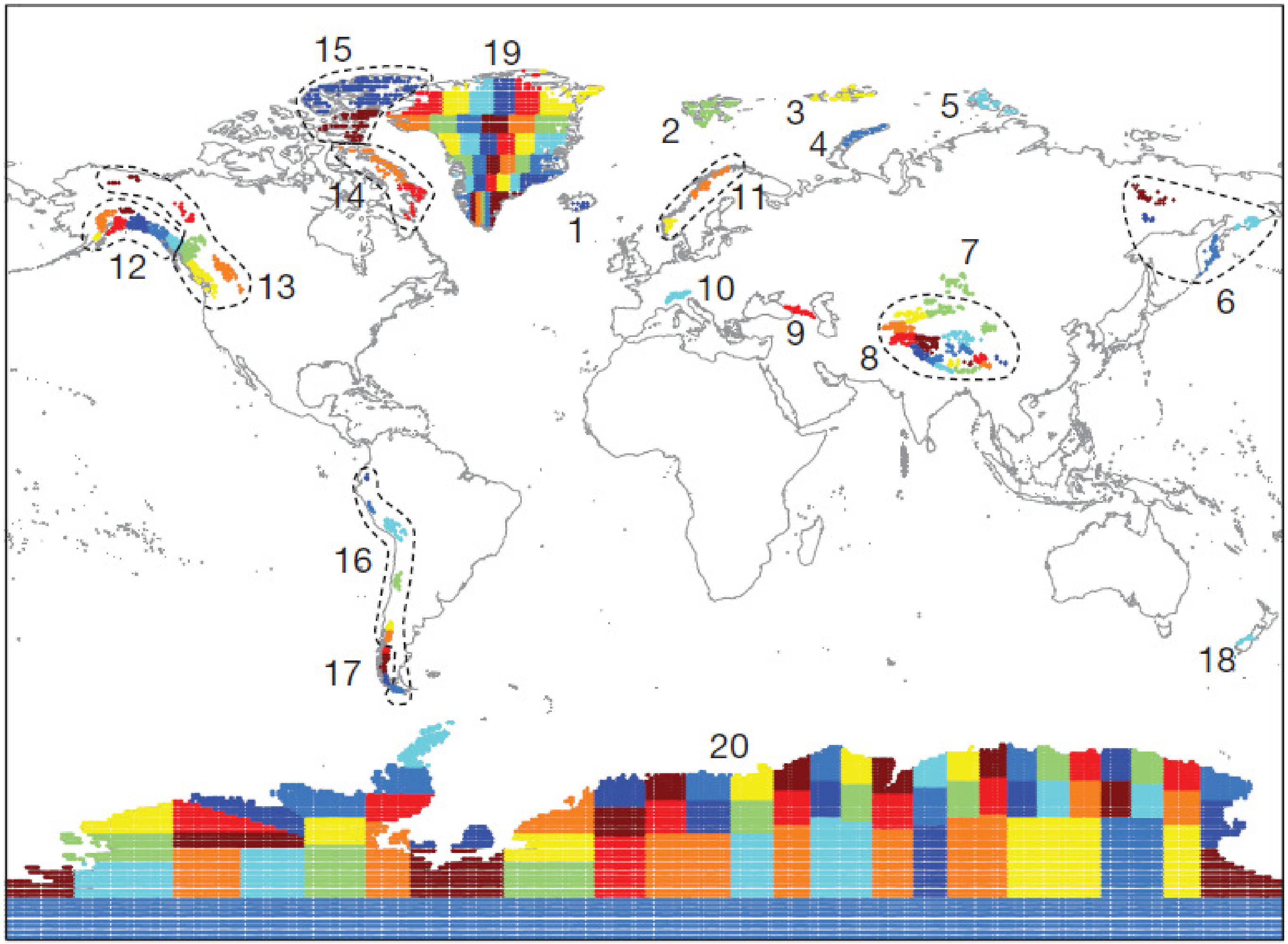

Mascons for the ice-covered regions considered here. Each coloured region represents a single mascon. Numbers correspond to regions shown in Table 1. Regions containing more than one mascon are outlined with a dashed line.

Jacob et al., 2012

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Region	Rate ($Gt\,yr^{-1}$)
1. Iceland	−11 ± 2
2. Svalbard	−3 ± 2
3. Franz Josef Land	0 ± 2
4. Novaya Zemlya	−4 ± 2
5. Severnaya Zemlya	−1 ± 2
6. Siberia and Kamchatka	2 ± 10
7. Altai	3 ± 6
8. High Mountain Asia	−4 ± 20
8a. Tianshan	−5 ± 6
8b. Pamirs and Kunlun Shan	−1 ± 5
8c. Himalaya and Karakoram	−5 ± 6
8d. Tibet and Qilian Shan	7 ± 7
9. Caucasus	1 ± 3
10. Alps	−2 ± 3
11. Scandinavia	3 ± 5
12. Alaska	−46 ± 7
13. Northwest America excl. Alaska	5 ± 8
14. Baffin Island	−33 ± 5
15. Ellesmere, Axel Heiberg and Devon Islands	−34 ± 6
16. South America excl. Patagonia	−6 ± 12
17. Patagonia	−23 ± 9
18. New Zealand	2 ± 3
19. Greenland ice sheet + PGICs	−222 ± 9
20. Antarctica ice sheet + PGICs	−165 ± 72
Total	−536 ± 93
GICs excl. Greenland and Antarctica PGICs	−148 ± 30
Antarctica + Greenland ice sheet and PGICs	−384 ± 71
Total contribution to SLR	1.48 ± 0.26 mm yr^{-1}
SLR due to GICs excl. Greenland and Antarctica PGICs	0.41 ± 0.08 mm yr^{-1}
SLR due to Antarctica + Greenland ice sheet and PGICs	1.06 ± 0.19 mm yr^{-1}

Uncertainties are given at the 95% (2σ) confidence level.

Inverted 2003–2010 mass balance rates.

Total contribution to Sea Level Rise (SLR): **1.48 mm/yr**

Jacob et al., 2012

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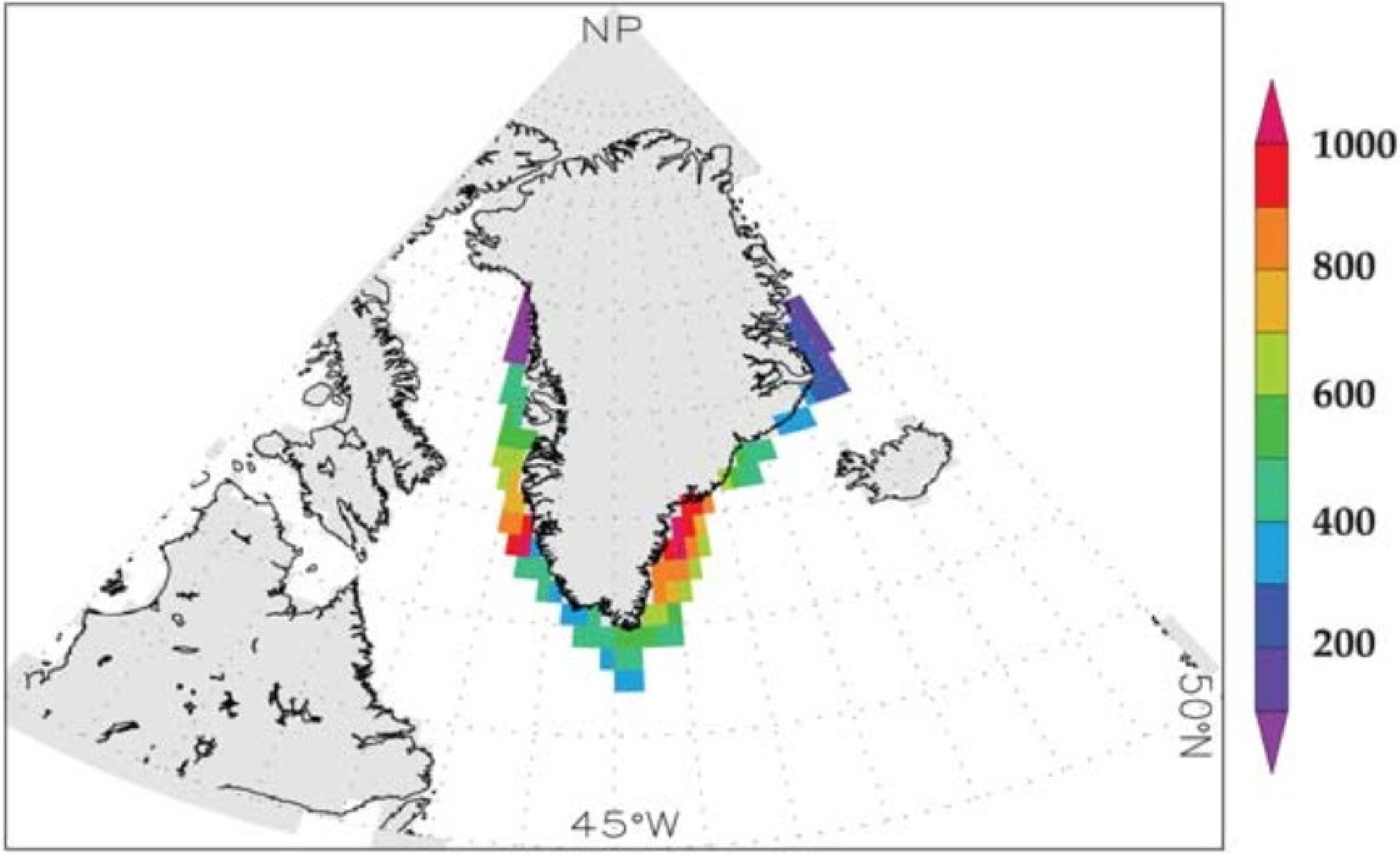

Surface fresh water flux anomalies (m^3/s) per model grid point associated with the mass loss of Greenland ice sheet and added to the NECEP/NCAR net freshwater forcing after division by the surface area of each grid cell. Stammer, 2008.

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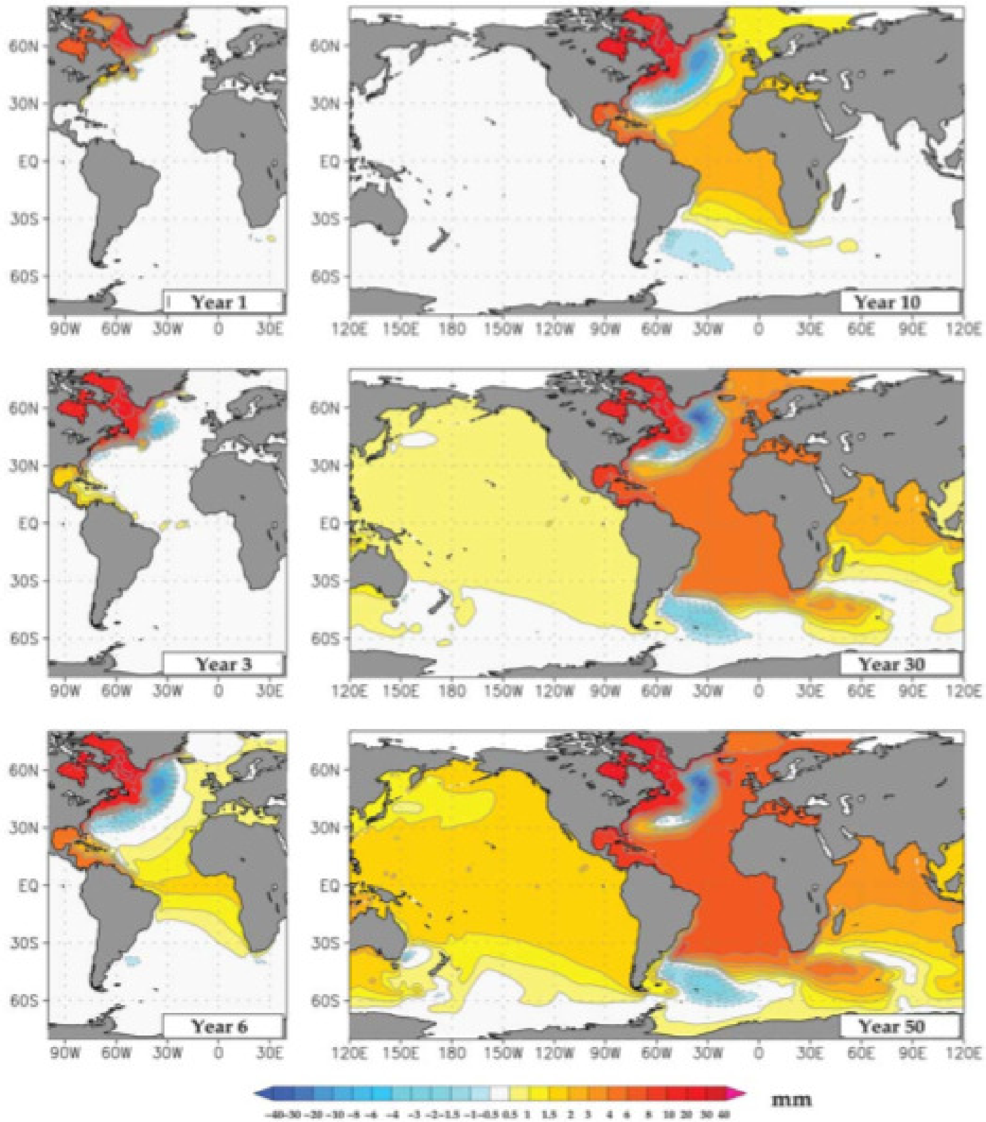
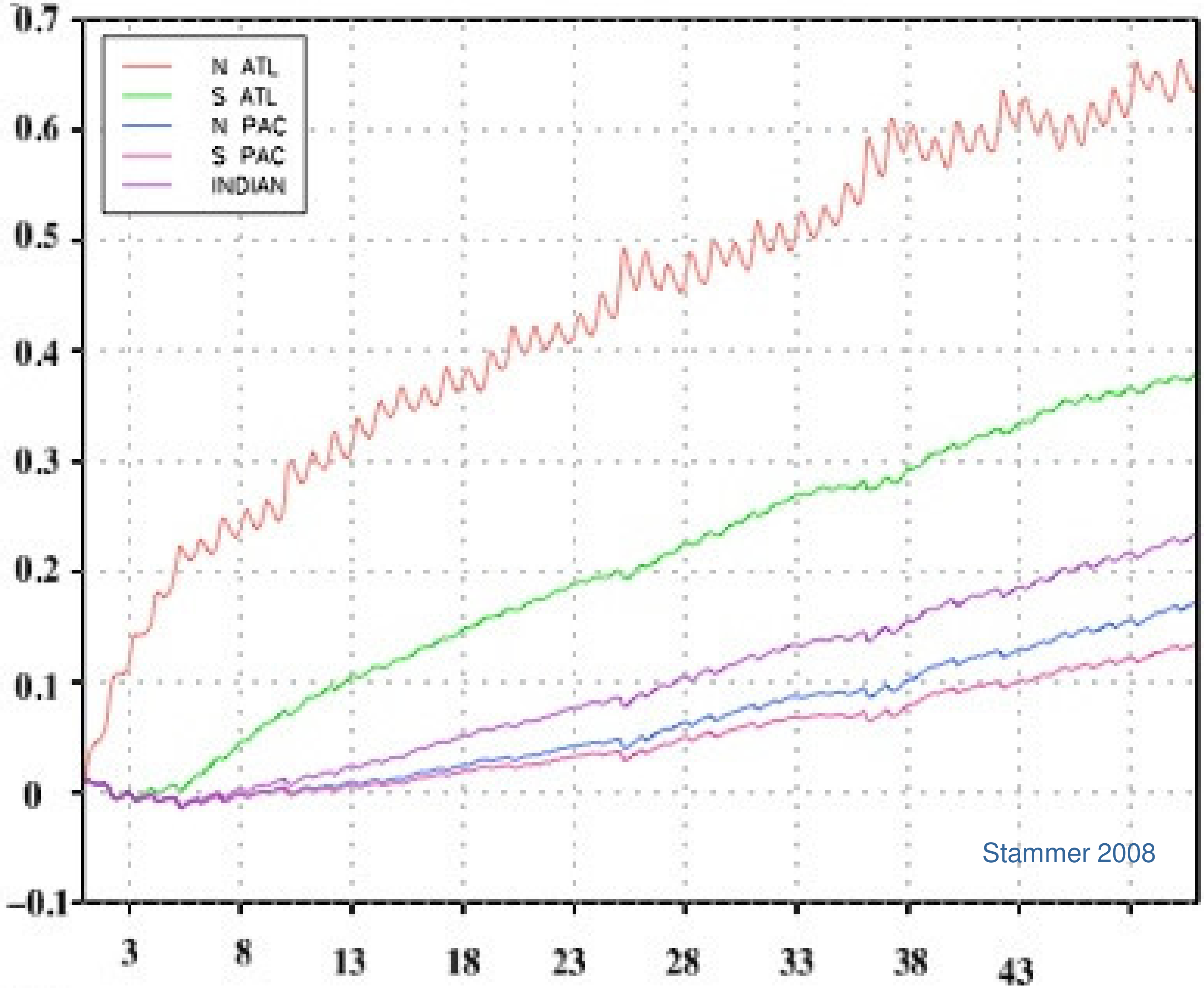
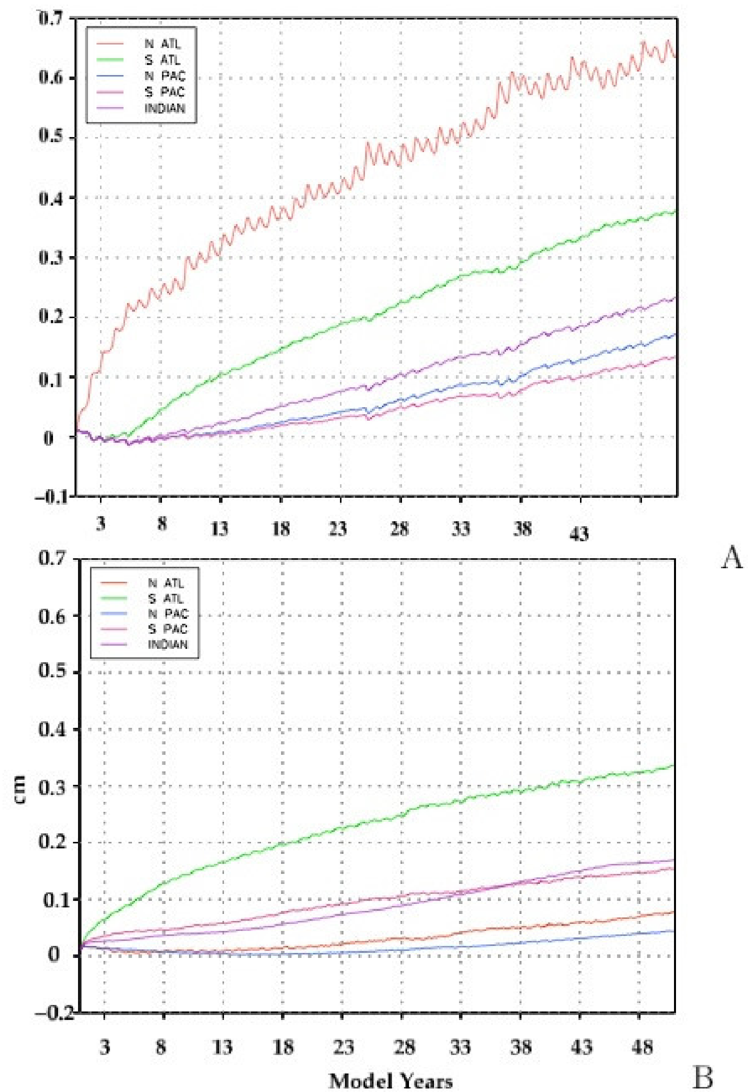


December-mean anomalies of SSH as they result from enhanced Greenland freshwater forcing. (left) SSH anomalies for the Atlantic from the years 1, 3, and 6. (right) Similar fields, but globally and for the years 10, 30, and 50.

Stammer 2008



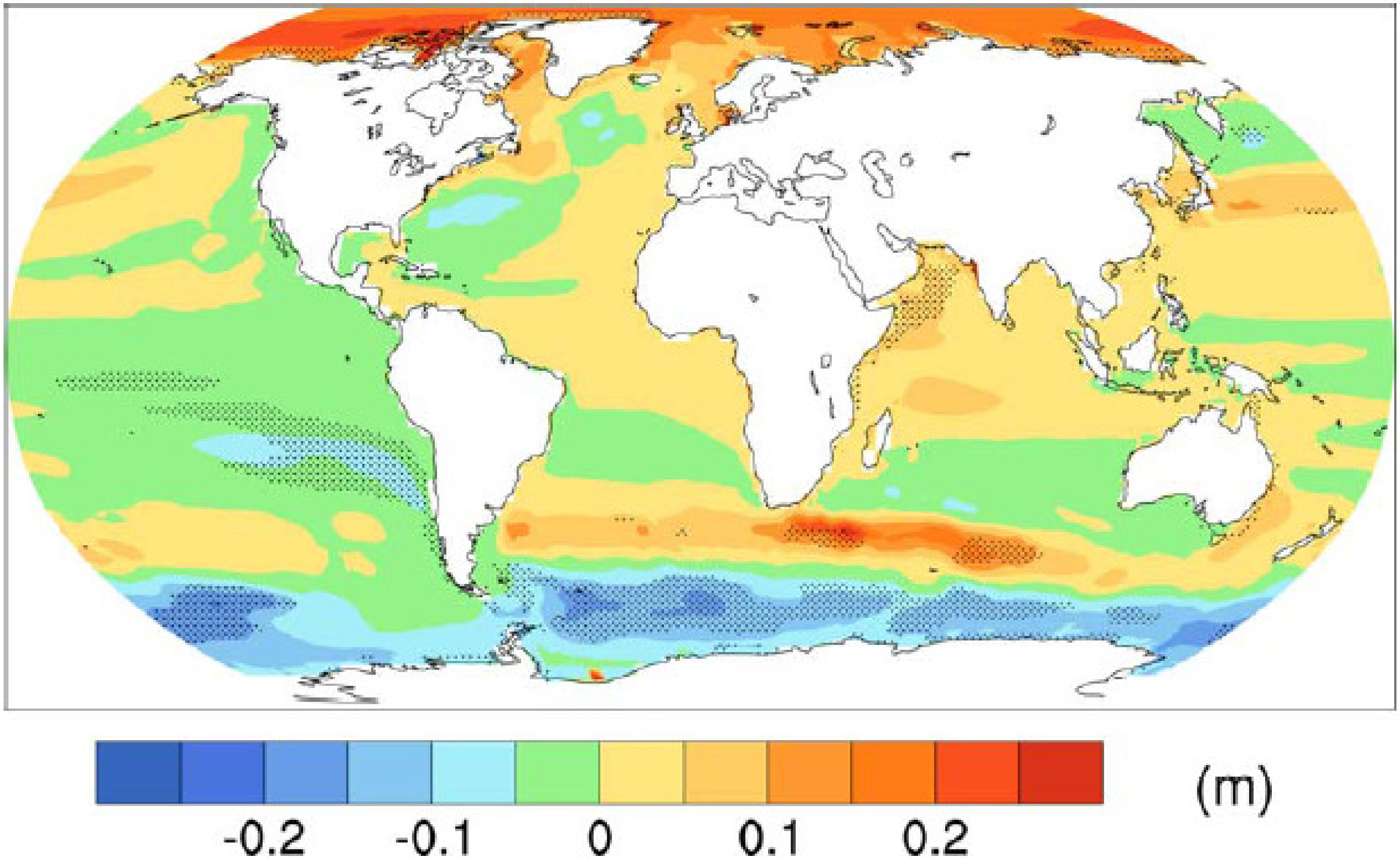
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
3
8
13
18
23
28
33
38
43
N ATL
S ATL
N PAC
S PAC
INDIAN
Stammer 2008



(a) Basin-integrated SSH anomalies resulting from the Greenland run, computed separately for the North Atlantic (red), the South Atlantic (green), the Indian Ocean (purple), and the North and South Pacific (blue and red, respectively). (b) Basin-integrated SSH anomalies resulting from the Antarctic run, computed separately for the North Atlantic (red), the South Atlantic (green), the Indian Ocean (purple), and the North and South Pacific (blue and red, respectively).

Stammer 2008

Projected sea level change is not globally uniform



Sea level change due to ocean density and circulation change during 21st century (2080-2099 relative to 1980-1999) under A1B, average of 16 AOGCMs, shown relative to global mean. Spatial variation is about 25% of global mean

Challenges

Improved glacier and ice sheet models where glacial outflow dynamics is included in global coupled models in order to assess impact of sea level change

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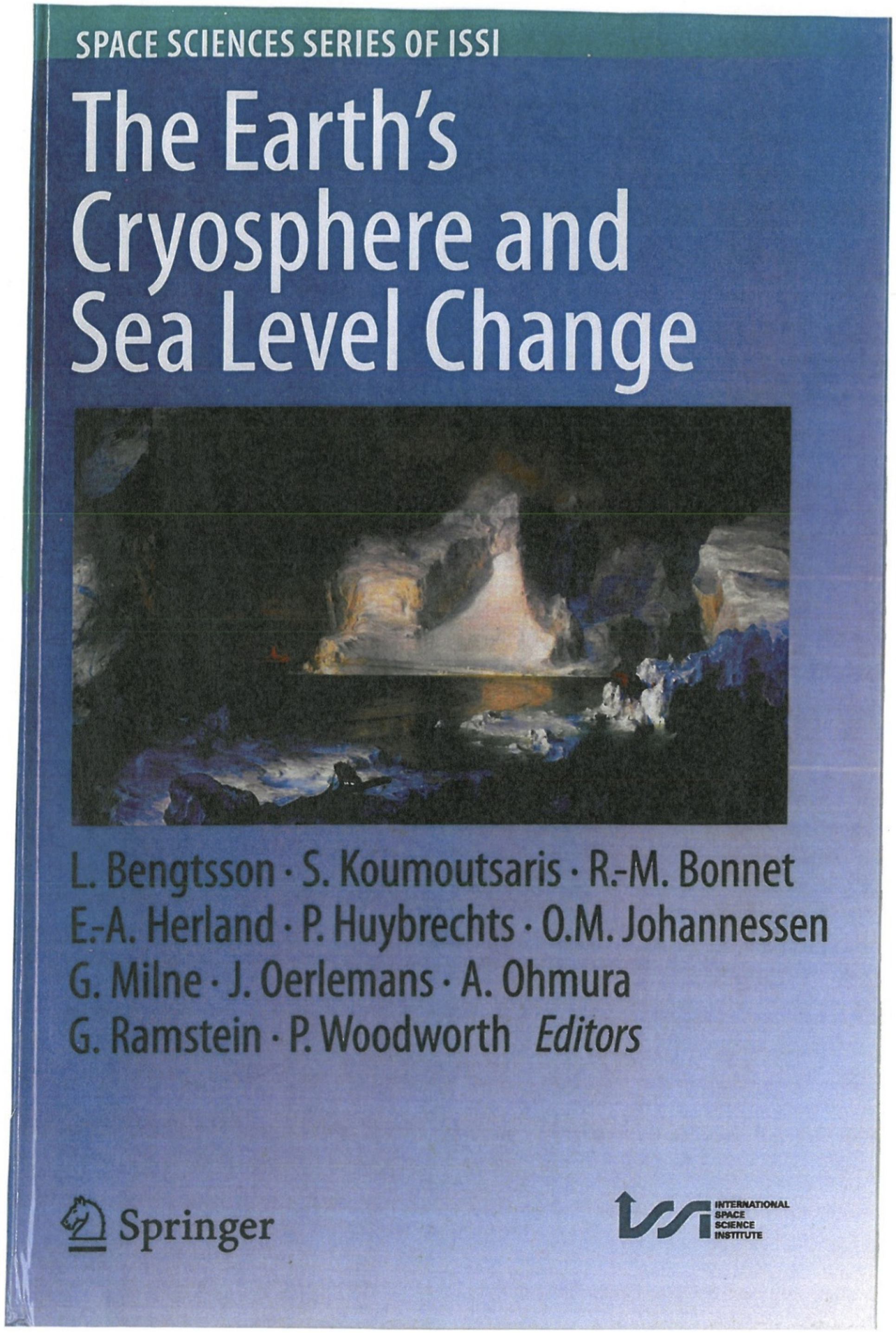

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RA sea level trends 1993 to 2003

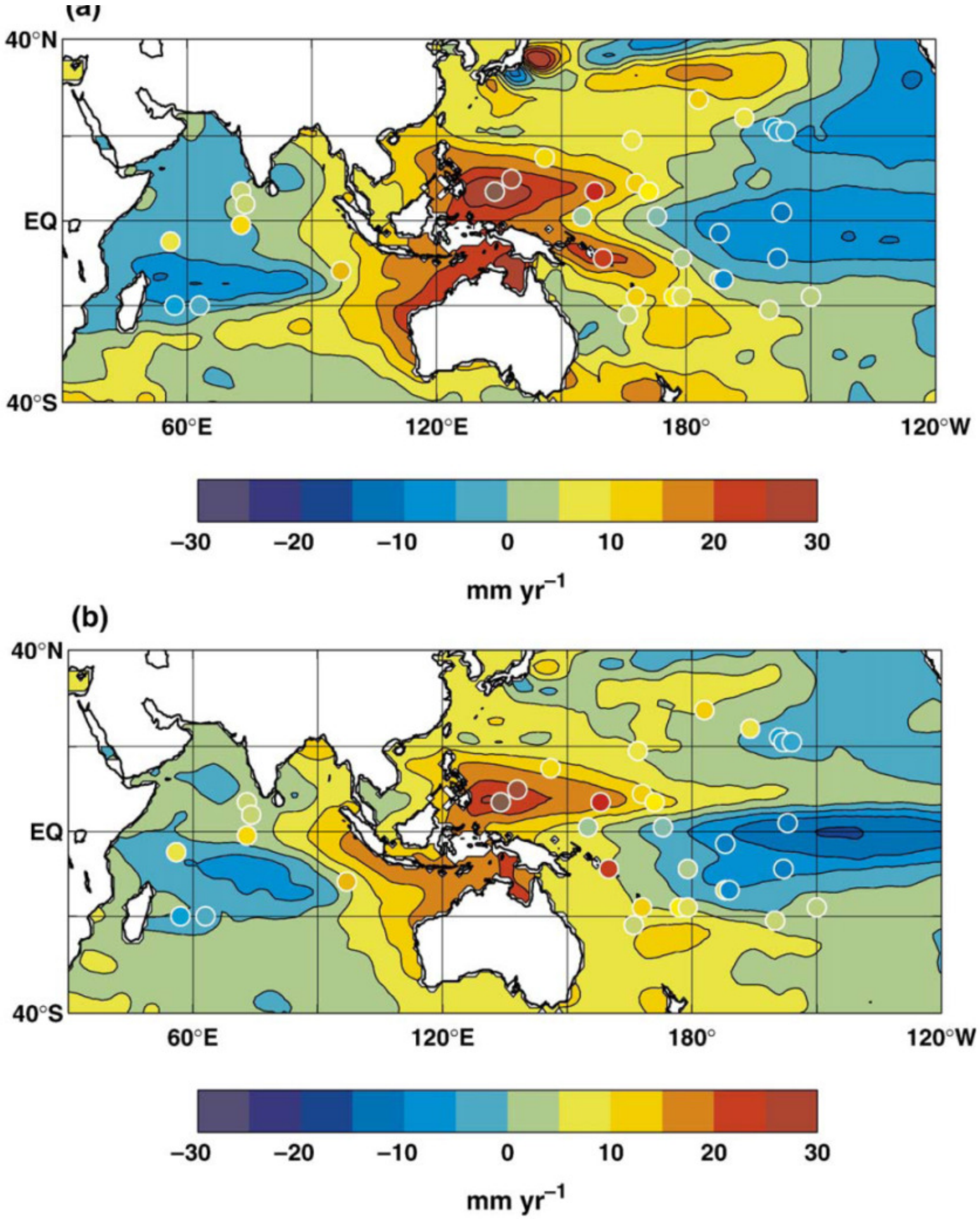

Fig. 2. Map of sea-level trends for (a) TOPEX/Poseidon data and (b) the reconstruction for 1993 to 2001. Tide-gauge trends for the same period are shown where available by the coloured dots.

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