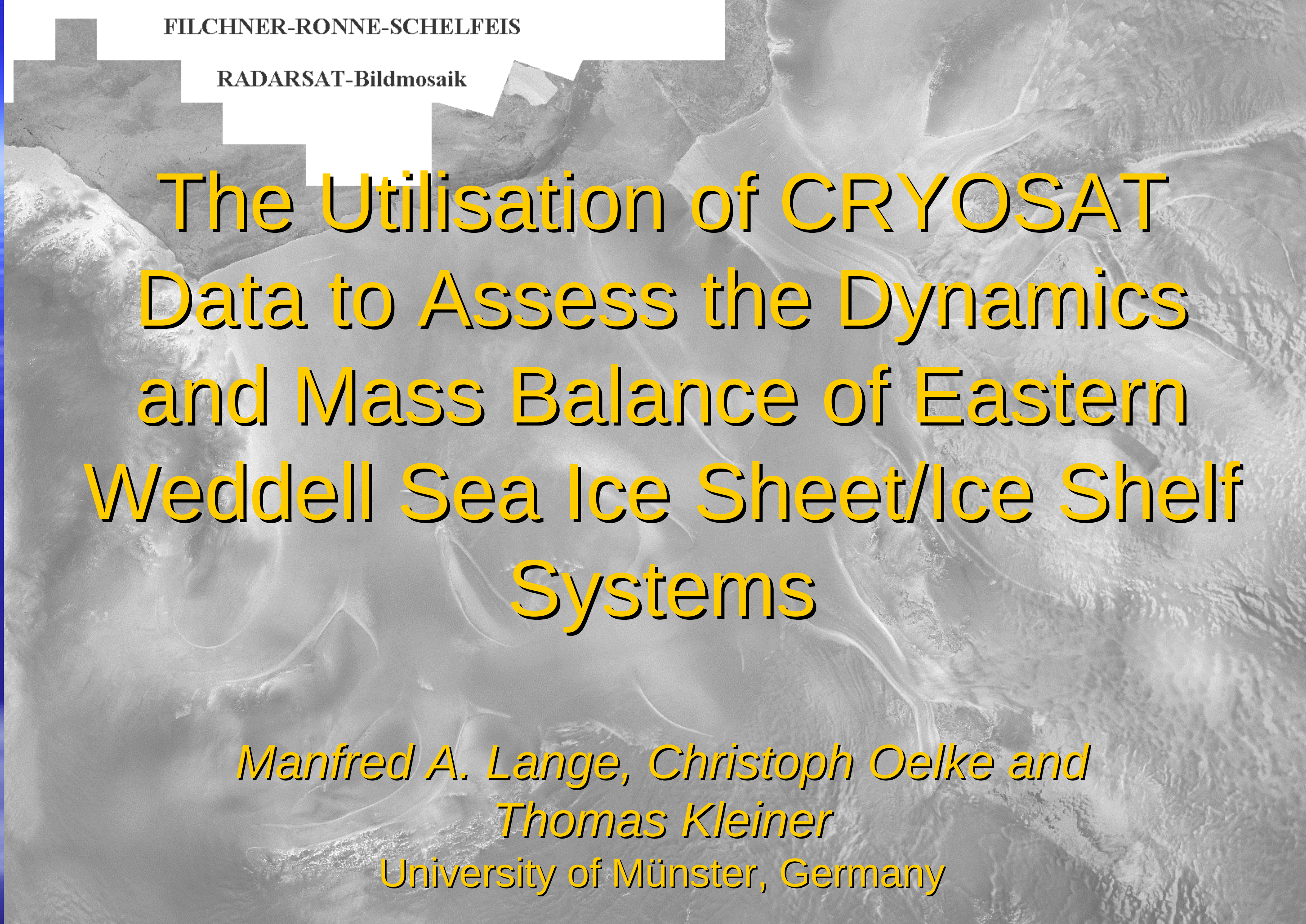


# The Utilisation of CRYOSAT Data to Assess the Dynamics and Mass Balance of Eastern Weddell Sea Ice Sheet/Ice Shelf Systems

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# Outline

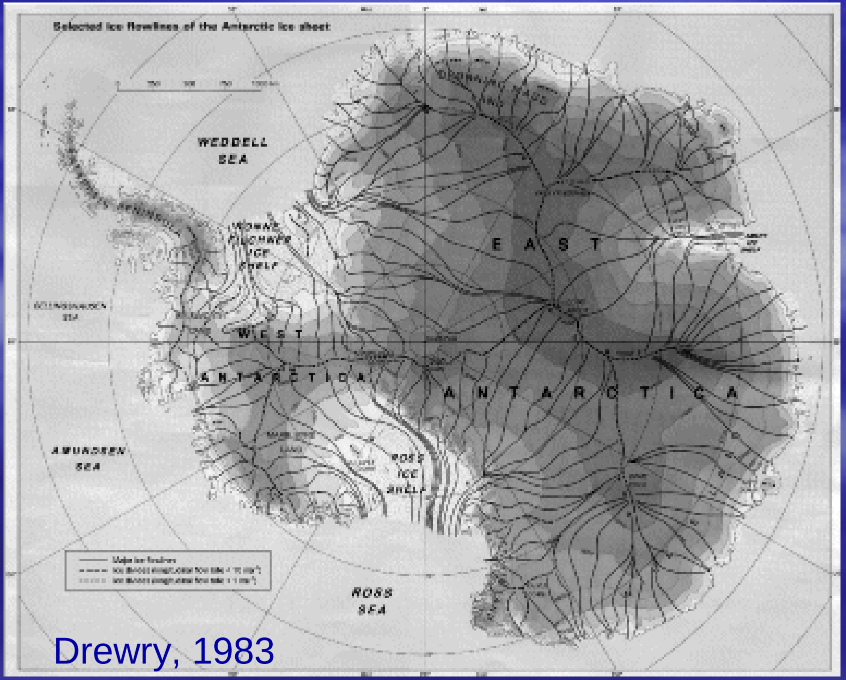
- Introduction/Rationale
- Methodologies
- Study region
- First results
- Perspectives

**Cooperation partners: for earlier and ongoing work: TU Dresden (R. Dietrich) for CRYOSAT related work: Norwegian Polar Institute (E. Isaksson) and University of Uppsala (V. Pohjola)**

Photo: Rückamp, 2005

# Introduction/Rationale

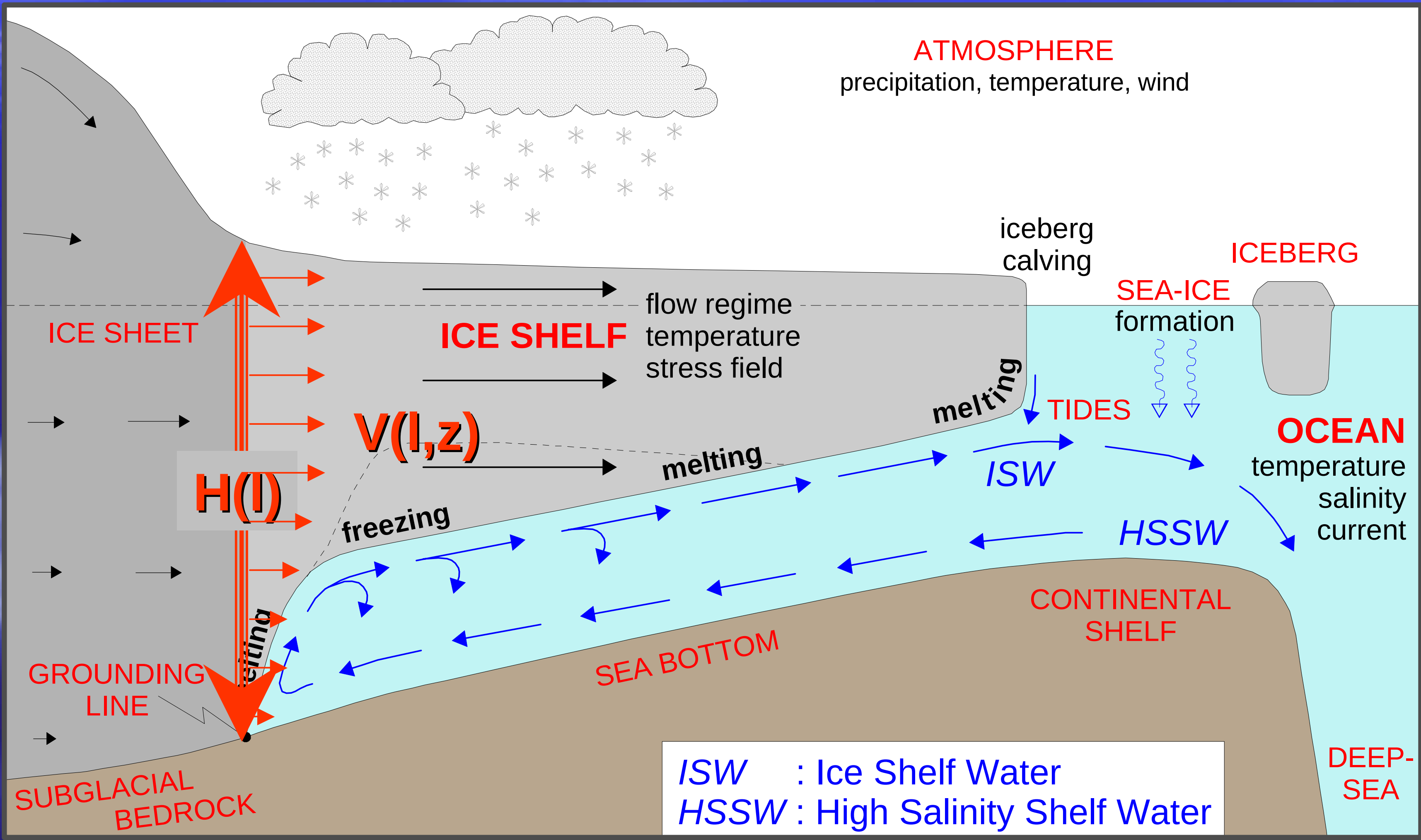
- Antarctic cryosphere is important indicator of global climate change
- Proximity of cryosphere to melting point ⇨ enhanced sensitivity
- Changes in the cryosphere ⇨ changes in global radiation budget ⇨ feedbacks to global climate system
- Mass balance changes ⇨ effects on hydrosphere (sea level)
- Enhanced calving/melting ⇨ changes in thermohaline circulation
- Inland-ice/ice-shelf systems particularly important




Drewry, 1983

# Mass Flux Across the Grounding Line

- Two major unknowns:
  - thickness distribution along the grounding line
  - vertical distribution of horizontal ice velocities along grounding line



# Methodology

- The (instantaneous) mass flux across the grounding line of an ice shelf of length Δl can be computed from

$$\dot{M}\Big|_{\Delta l} = \int_{l_0}^{l_0+\Delta l} \int_{0}^{H(l)} v(z,l)\,\rho(z,l)\,dz\,dl$$

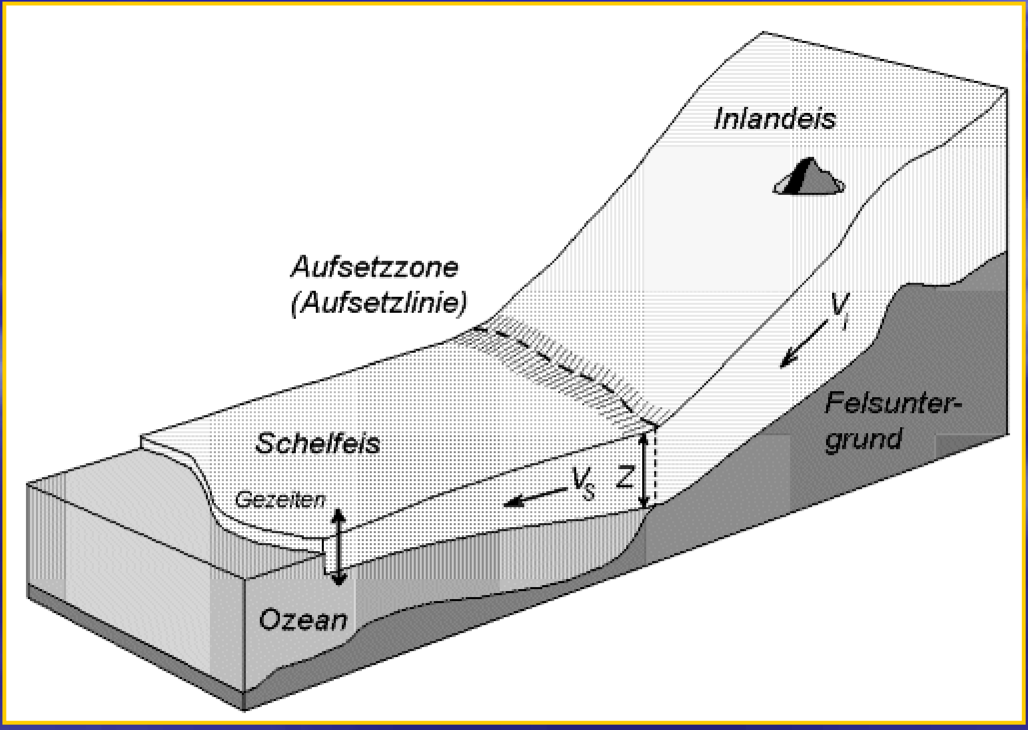
- In this equation, it is assumed that horizontal ice velocity v and density ρ do not vary with time
- ρ is usually replaced by a mean value
- This leads to the following simplification:

$$\dot{M}\Big|_{\Delta l} = \bar{\rho} \cdot \int_{l_0}^{l_0+\Delta l} \int_{0}^{H(l)} v(z,l)\,dz\,dl$$

- The two unknowns v(z,l) and H(l) are difficult to determine directly

# Methodology

- Solution (at least partly) ⇨ effective integration of numerical modeling and remote sensing data
- Modeling: 3D ice shelf model
- Remote sensing: radar interferometry; altimetry
- ⇨ remote sensing data provide boundary conditions for modeling/inversion
- Model results to be confirmed by in-situ ground-based measurements



# Ice Shelf Modeling

- Numerical ice dynamics modeling: basic equations

$$\nabla \cdot \underline{\underline{\sigma}} + \rho g \vec{n}_z = 0$$

$$\underline{\underline{\sigma}} = 2\nu \underline{\underline{\dot{\varepsilon}}}$$

$$\nu = \frac{\overline{B}_z}{2\dot{\varepsilon}^{1+\frac{1}{3}}}$$

$$\dot{\varepsilon} = A\sigma^n \; (Glen's \; flow \; law)$$

$$\dot{\varepsilon}_{xx} = \frac{\partial u}{\partial x}; \dot{\varepsilon}_{yy} = \frac{\partial v}{\partial y}; \dot{\varepsilon}_{zz} = -\dot{\varepsilon}_{xy} - \dot{\varepsilon}_{yy}; \dot{\varepsilon}_{xy} = \tfrac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

$$\frac{\partial H}{\partial t} = -\nabla(\vec{u} H) + \dot{a} + \dot{b}$$

$\underline{\underline{\sigma}}$ = Stress tensor; $\underline{\underline{\dot{\varepsilon}}}$ = deformation rate tensor; $\nabla$ = Laplace – Operator

$\rho$ = ice density (981 kg/m$^3$); $g$ = gravitational acceleration; $\vec{n}_z$ = unit vector in z – direction

$\nu$ = effektive viscosity; $\overline{B}_z$ = vertically avraged strength; $\dot{\varepsilon}$ = deformation rate

$\sigma$ = stress; $A$ = temperatur – depedant activation energy; $n$ = parameter (usually = 3)

$H$ = ice thickness; $t$ = time; $\vec{u} = (u, v)$ = velocity in x – y – plane; $\dot{a}$ = accumulation rate; $\dot{b}$ = melt rate

# Ice Shelf Modeling

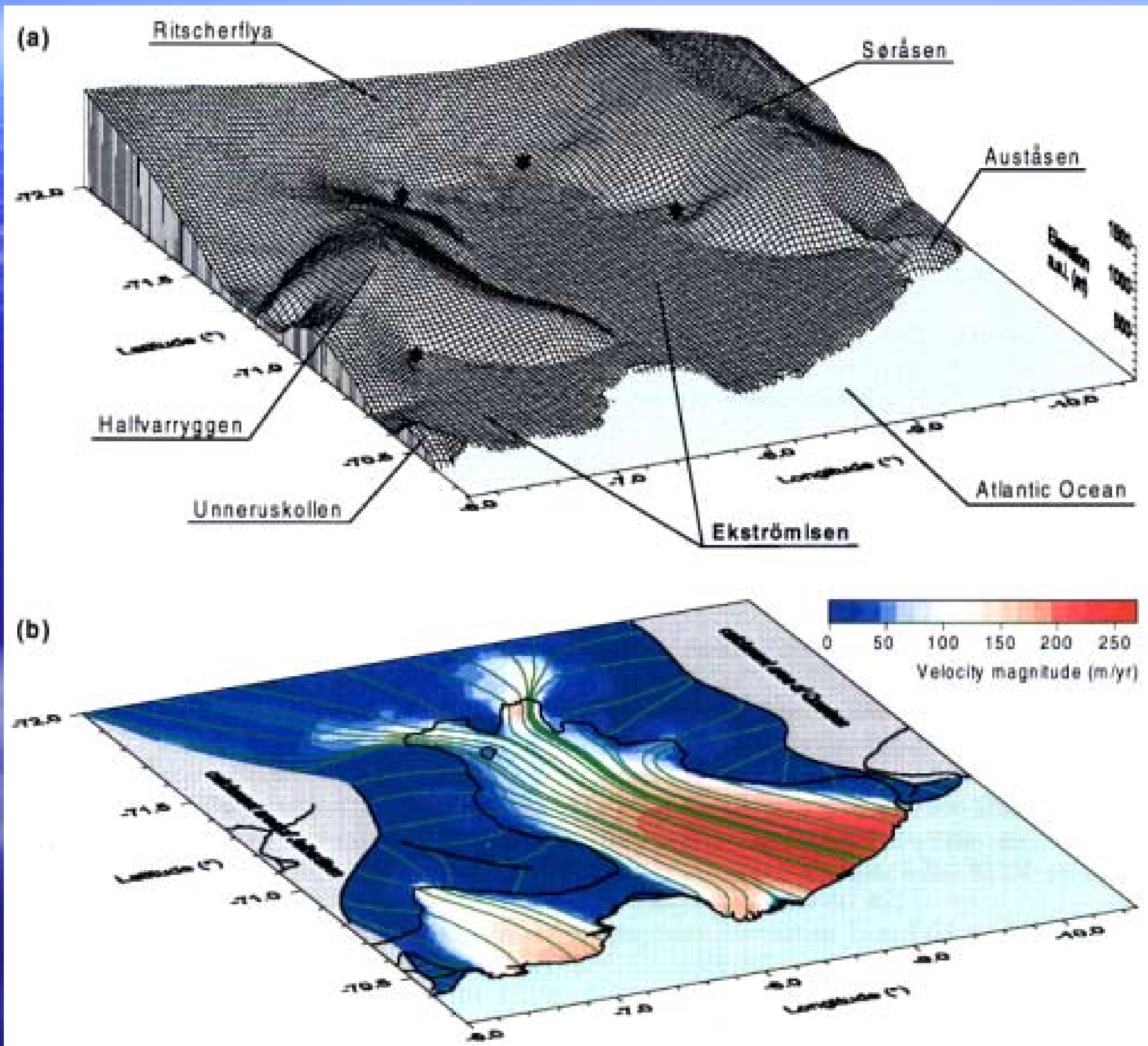
**Model equations**
- Thermo-mechanical budget equations
- Flow law; material properties

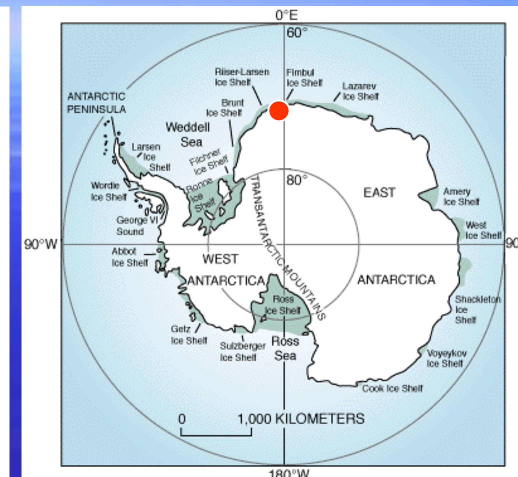
**Boundary conditions**
- Ice geometry: extent in x-y-plane; thicknesses, surface slope, grounding line position, ice inflow at margins
- Surface accumulation and bottom melting
- Bedrock: (ocean bottom) topography

**Numerical solution**
- 3D finite difference model

**Results**
- $u\,(x,y,z)$, $\tau_{i,j}$, $T(x,y,z)$, $H$

# Ice Shelf Modeling



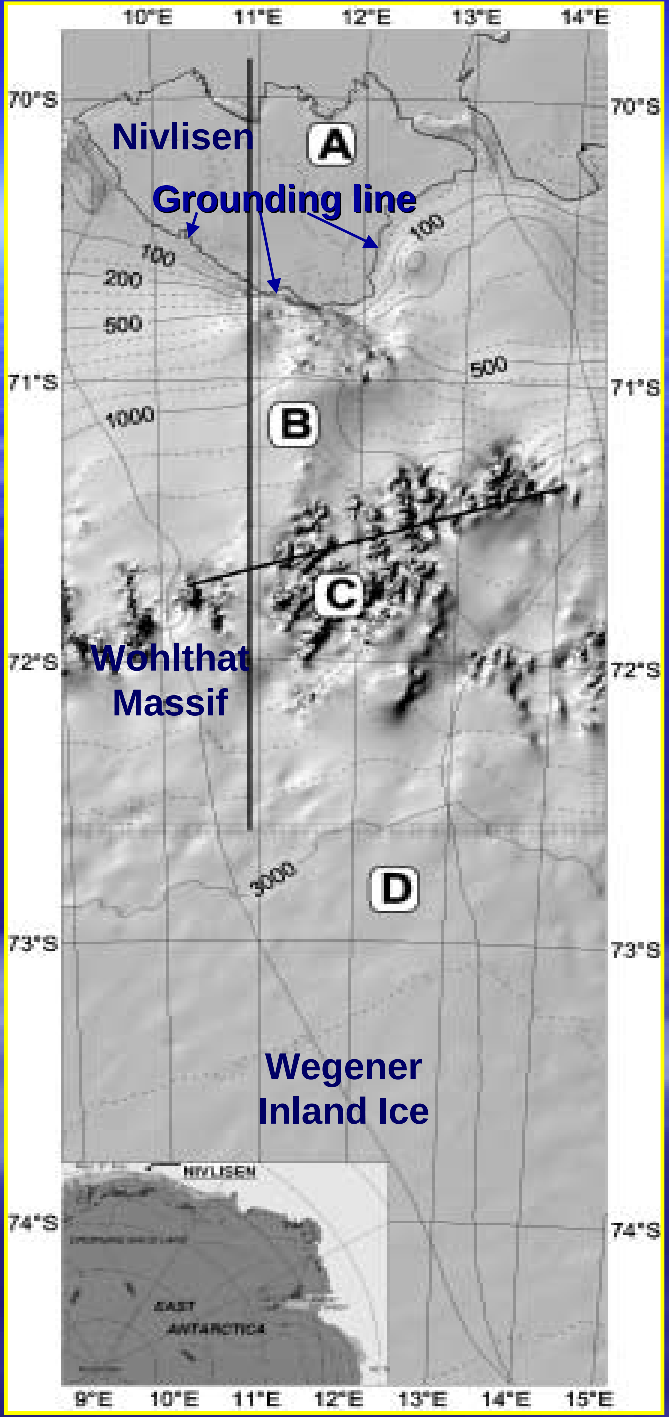



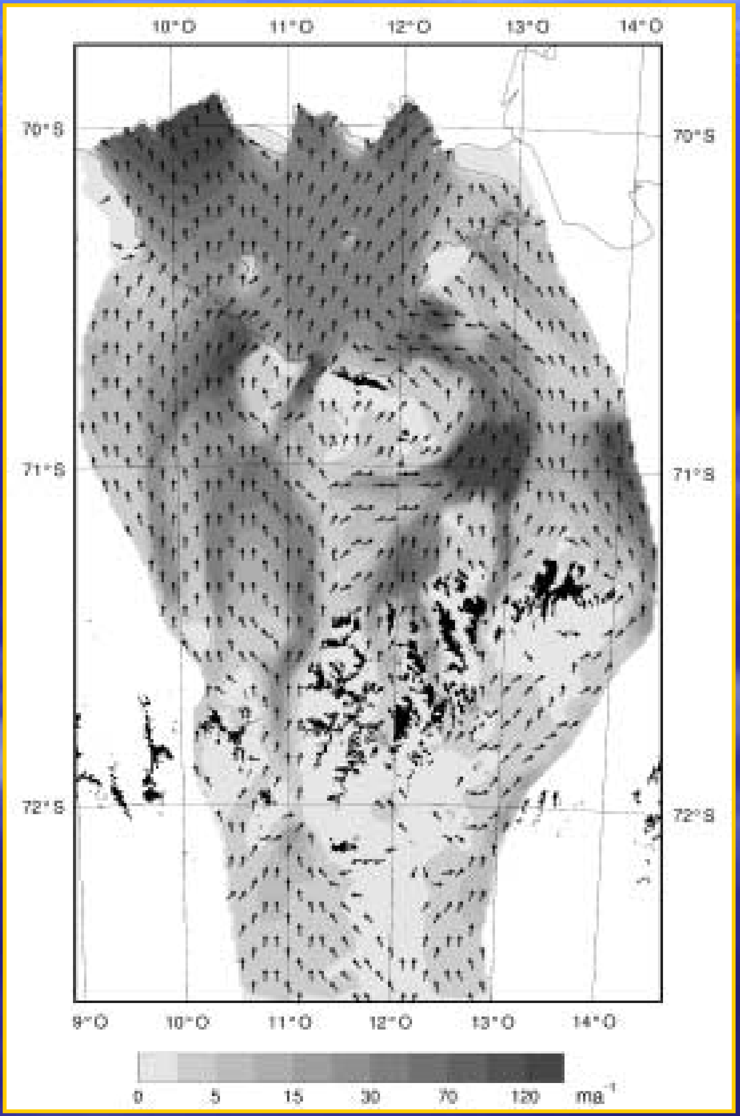

Surface topography (a) as derived from airborne altimetry for the Ekströmisen and modeled vertically averaged ice velocities in the inland ice drainage region and the ice shelf and flow lines (from Sandhäger, 2000)

# Ice Shelf Modeling

- We need ice shelf dynamics parameters at the grounding line, i.e., the transition between inland ice and ice shelf
- While we do run coupled inland-ice-ice-shelf models, the transition/grounding line zone remains a challenge
- Remotely sensed data serve as both, validation values and boundary conditions for inverse solutions aimed at determining the two unknowns v(z,l) and H(l) (through surface topographies)
- In addition, remote sensing data, in particular radar interferometry, allows precise determination of grounding line position

# Inland-Ice-Ice-Shelf Modeling



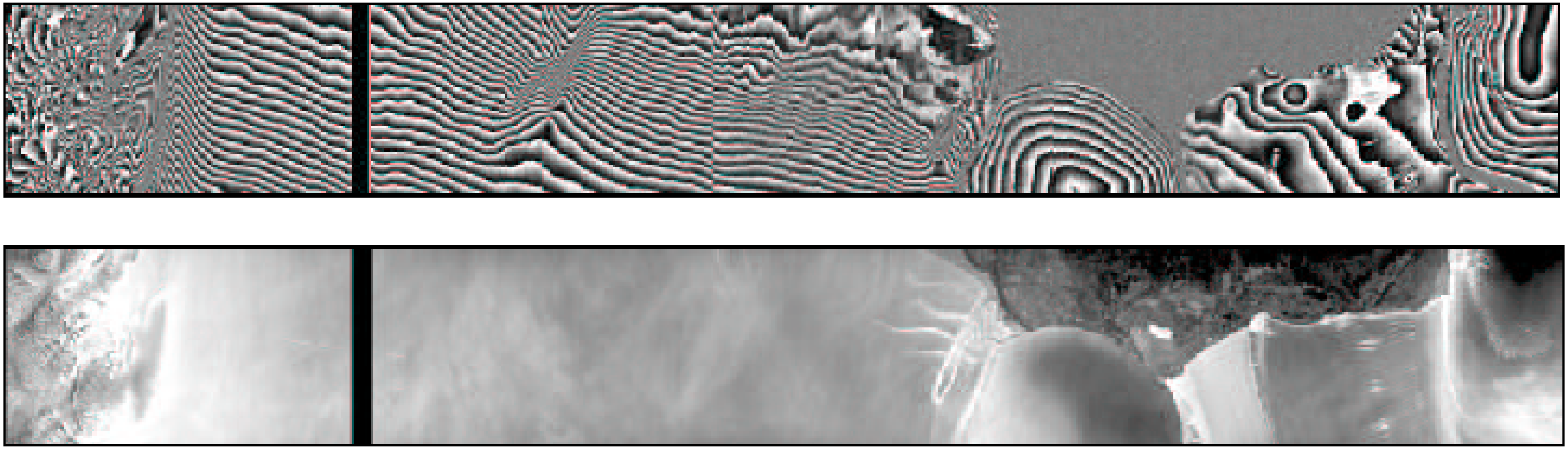




The Inland-Ice/Ice-Shelf system from the Nivlisen Ice Shelf to the Wegener Inland Ice (left); modeled, vertically integrated ice velocities for the entire system; in order to match observed velocities, we had to introduce spatially varying boundary conditions at the ice-bedrock interface in the region of the Wohlthat Massif

# Satellite Remote Sensing

- Satellite data provide basic information to be utilized in our project
  - Radar altimetry ⇨ freeboard heights of the ice shelf
    ⇨ ice shelf thicknesses (indirect)
  - Radar interferometry ⇨ horizontal ice velocities at the surface
    ⇨ position of the grounding line/zone
- However, there are a number of limitations associated with this approach:
  - Isostatic equilibrium has to be assumed
  - Interferometrically derived horizontal ice velocities at the surface can reliably only be obtained in 'flat' parts of the ice shelf, i.e., only through a limited extent in the region of the grounding zone
- Thus, we employ the following assumptions/remedies
  - isostatic equilibrium is assumed for 'most' of the ice shelf
  - Depth-independent ice velocities are 'extended'/''interpolated' towards the grounding line
  - Feature tracking as a means to derive ice velocities in the grounding zone

# Satellite Remote Sensing



**Parts of the Ronne-Filchner-Ice Shelf as seen in nine scenes. The black bar indicates a data gap.**

**The images shows from left to right: the Orville Coast at the Antarctic Peninsula, the Ronne Ice Shelf, Berkner Island an the Filchner Ice Shelf with the adjacent Weddell Sea to the North and the Prinzregent-Luitpold-Land to the East.**

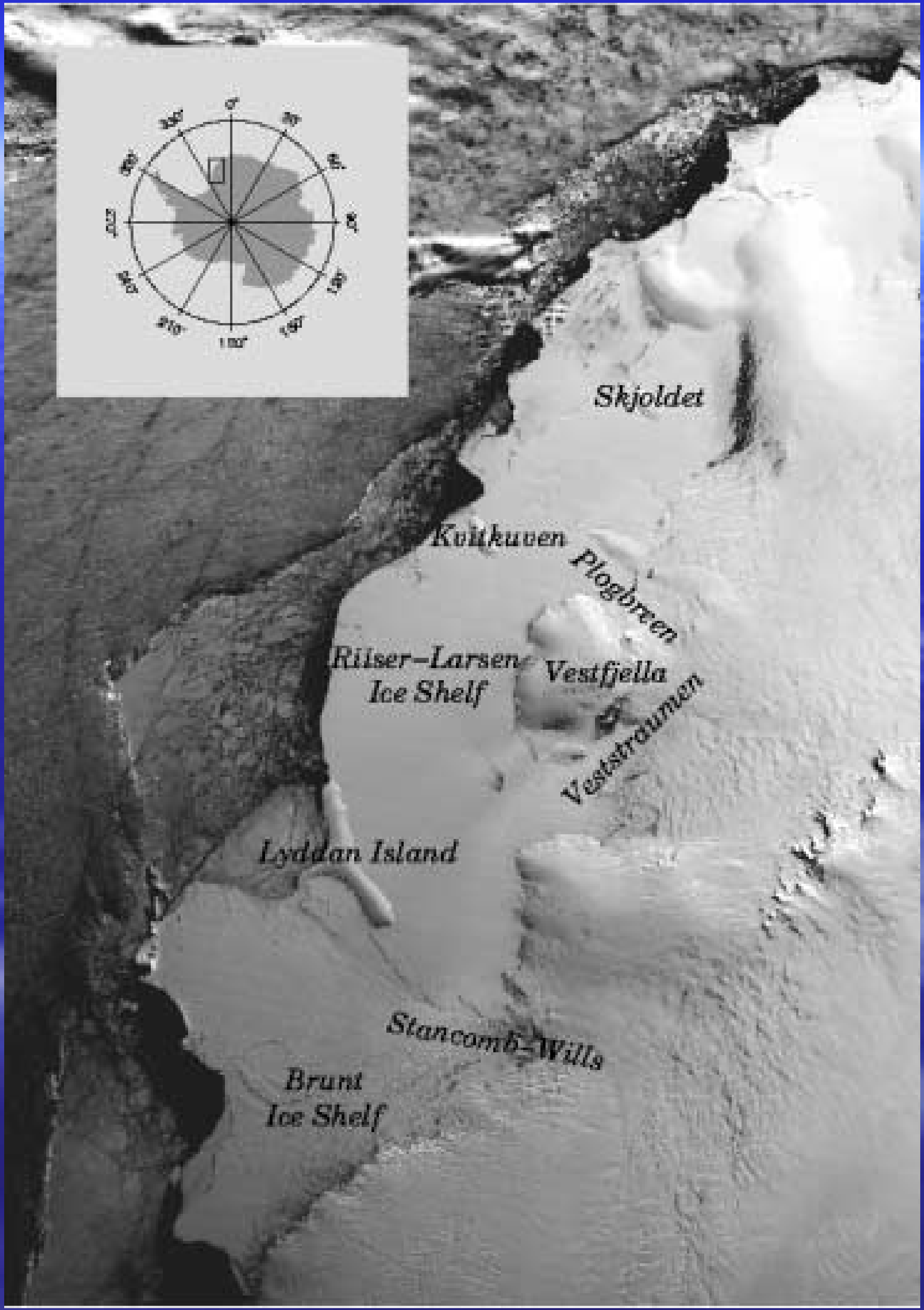
**Top: Interferogram; since the scenes have been processed separately, phase shifts between adjacent scenes are readily visible**

**Bottom: Amplitude (24.01.94, ERS-1 SAR).**

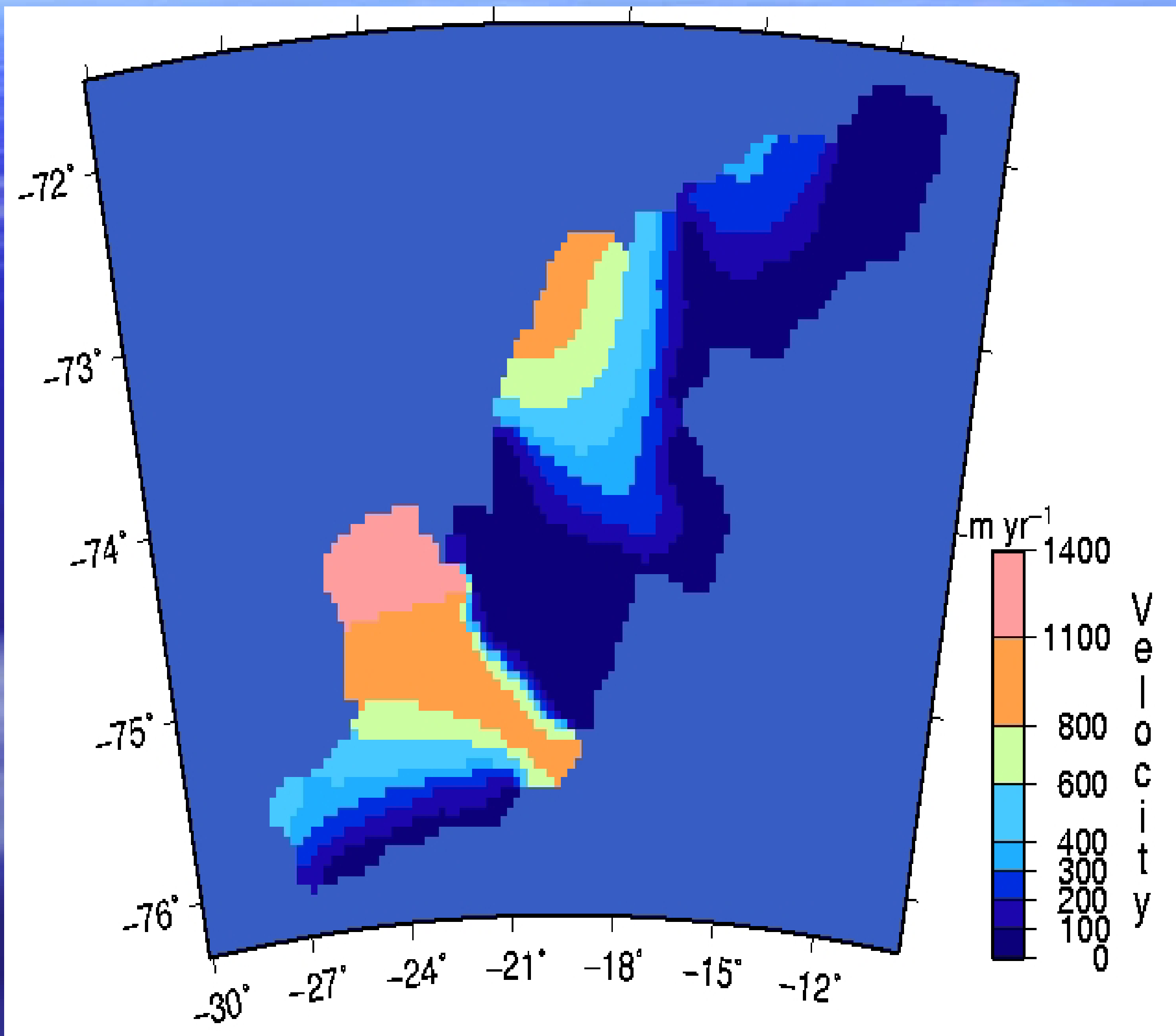
**[Source: Thiel, Univ. Stuttgart]**

# Study Region

The Riiser-Larsen Ice Shelf (RLIS) and the Brunt Ice Shelf (BIS) represent a fairly complicated system, which is on the one hand strongly influenced  by the ice streams (Plogbreen and Veststraumen for RLIS and the Stancomb Wills Ice Stream for BIS) and on the other by ice rises and ice islands (i.e., Skjoldet and Kvitkuven for RLIS and Lyddan Island for BIS and to some extent RLIS). In addition, because of differential ice movement, large shear zones have been developed, which are characterized by heavy crevassing and drastically altered ice velocities compared to the adjacent ice masses (in particular the area north-east of the Stancomb Wills Ice Stream of BIS). Finally, south of the Stancomb Wills Ice Stream significant fractions of (formerly) landfast (sea) ice has been incorporated into the ice shelf, thus influencing its flow regime.



# First Results

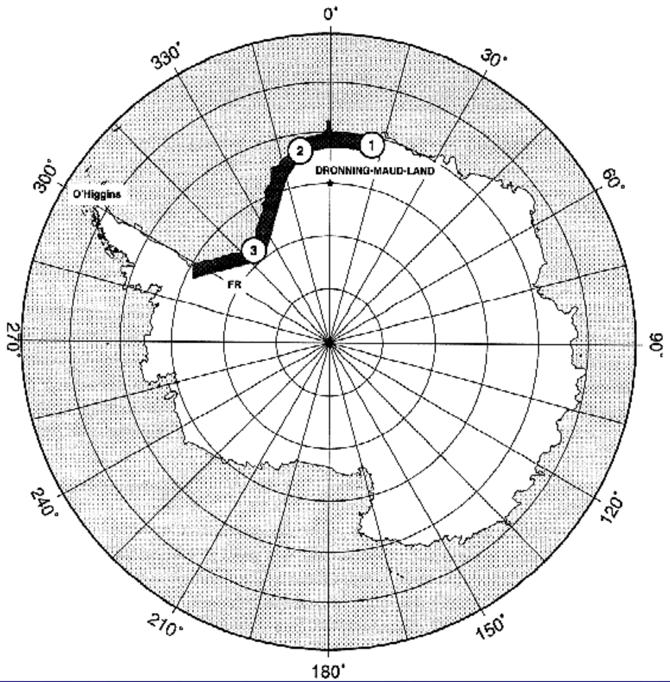



The dynamics of the RLIS and the BIS have been modeled at a resolution of 5km x5km. Surface topographies were derived from a careful analysis of the BEDMAP data base; ice thicknesses were derived by assuming isostatic equilibrium within the ice shelves.

The vertically averaged velocities thus obtained demonstrate that the flow regimes of are quite different for each ice shelf. While the dynamics of the RLIS seems to be mainly influenced by the surface slope of the ice shelf and the two ice rises, movement of the BIS appears to be dominated by the Stancomb Wills Ice Stream

# CRYOSAT Project

- The major goal of our project lies in developing a <u>modeling platform</u> that allows determination of the key parameters v(z,l) and H(l) and thus the mass flux across the grounding line of various ice shelves as well as the position of their grounding lines <u>solely on the basis of remote sensing</u>
- This will enable a continuous monitoring of the mass flux and thus of major elements of the overall mass balance of Antarctica
- We intend to utilize CRYOSAT for H(l) and ERS-data and ENVISAT for v(z,l) and grounding line position
- Ground-truthing is to be carried out on RLIS by our Scandinavian colleagues



# Perspectives

- The mass flux across the grounding lines of Antarctic ice shelves has a major bearing on the overall mass balance of the Antarctic Ice Sheet
- Direct estimates of this quantity are extremely difficult and not readily feasible
- A combination of numerical inland-ice/ice-shelf modeling and basic parameters derived by satellite remote sensing offers a promising opportunity to monitor mass fluxes on a continuous basis
- However, the characteristics of the grounding zone present challenges to both remote sensing and numerical modeling
- We expect that the CRYOSAT altimeter measurements will yield significantly improved surface topographies and thus contribute to more realistic modeling results