Development of WRF-ice for Surface Mass Balance Modeling over Antarctic Peninsula

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Introduction

- The Antarctic Peninsula (AP) presents rapid environmental changes
- Progress has been made in the use of regional modeling to simulate surface mass changes over ice sheets but focus has been over Greenland ice sheets.
- Adaptations to those models have included treatment of meltwater percolation, retention and refreezing of snow and underlying firn, parameterizations for broadband snow albedo, and snowdrift processes and sublimation.

WRF-ice description

- Implements various ice and snow processes to enhance the default WRF model’s ability to simulate the surface mass balance over the ice surface.

- WRF-ice includes
  - Ice Sheet thermodynamics
  - Sea-ice thermodynamics
  - Snow processes
    - Blowing snow
    - Broadband snow albedo parameterization
    - Snow density changes

Model Description

- **Ice Sheet (Vionnet et al. 2012)**
  - Extends single layer snow model from Noah Land Surface Model (LSM) to multi-layer discretization.
  - The ice sheet is treated as a mixture of snow and ice, changing gradually from pure snow at the surface to pure ice as the bottom of the snow layer depth
  - Includes firn processes such as refreezing and percolation
  - Non-freezing snowmelt is treated as runoff where 13% of liquid water can be stored inside snow through percolation
- **Sea ice**
  - Based on Zhang and Zhang (2001) thermodynamic sea ice model
  - Single layer of pure snow over sea ice.
  - All snowmelt is treated as runoff flowing into ocean.

Model Description

- Energy balance at the snow surface and layers is defined as:

$$Q_{sfc} = Q_{sfc} \downarrow - G_i \downarrow + F_i^{rfz} = 0$$

where $Q_{sfc} \downarrow$ is the surface heat flux, $G_i \downarrow$ snow layer conductivity, and F_i^{rfz} latent heat released from refreezing. The subscript i represent the layer

- Surface heat flux is defined as:

$$Q_{sfc} \downarrow = H_{lat} \downarrow + H_{sen} \downarrow + R_{LW} \downarrow + (1 - \alpha_{sfc}) R_{SW} \downarrow - \epsilon_{sfc} R_{sfc} \uparrow$$

  - $H_{lat} \downarrow$ is the latent heat flux
  - $H_{sen} \downarrow$ the sensible heat flux
  - $R_{LW} \downarrow$ the downward long-wave radiation flux
  - $R_{SW} \downarrow$ the downward short-wave radiation flux
  - $R_{sfc} \uparrow$ the upward long-wave radiation flux
  - ϵ_{sfc} the surface emissivity
  - α_{sfc} the surface albedo.

- Over sea ice $F_i^{rfz} = 0$.

Model Description

- The conductive heat flux of snow is defined as

$$G_i \downarrow = \frac{k_s}{h_{si}}\left(T_i - T_{ij}\right)$$

  - k_s the thermal conductivity of snow
  - h_{si} snow depth of the layer
  - T_i temperature of the layer
  - T_{ij} temperature of the interface between layers

- At the bottom layer or over sea ice, T_{ij} is equal to the temperature of the underlying ice.

- If the snow surface temperature exceeds the melting point of snow, the temperature of the snow is fixed to the melting temperature of snow, T_s^{mlt}, and the residual snow surface heat flux, ΔQ_{sfc}, is then used for melting,

$$F_i = min\left(0, \frac{\Delta t\ \Delta Q_{sfc}[T_s^{mlt}]}{\rho_s L_{mlt}}\right)$$

  - ρ_s snow density
  - L_{mlt} latent heat of fusion

Model Description - Snow

- **Snow Processes – Blowing Snow (Lenaerts et al. 2012)**
  - Incorporates PIEKTUK-D into the PBL section of WRF
  - Blowing snow is present whenever 10m wind speed exceed following threshold:
  $$U_t = U_{t0} + 0.0033(T_a + 27.27)^2$$
  - Saltation layer is assumed to develop instantaneously thus we specify the saltation blowing snow mixing ratio to be vertically homogenous:
  $$q_{b_{salt}} = 0.385\,(1 - U_t/U_{10})^{2.59}/u_*$$
  - Suspension layer boundaries lies between
  $z_{lb} = \left[z_r^{-0.544} + \left(ln\frac{q_{b_{salt}}\rho}{\rho_r}\right)/1.55\right]^{-1.838}$ and 1000m

Model Description - Snow

- **Snow Processes – Blowing Snow (Cont.)**
  - The model predicts the evolution of blowing snow mixing ratio and the blowing snow number concentration through the following equations

$$\frac{\partial q_b}{\partial t} = \frac{\partial}{\partial z}\left(K_b \frac{\partial q_b}{\partial z} + \nu_b q_b\right) + S_b$$
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial z}\left(K_N \frac{\partial N}{\partial z} + \nu_N N\right) + S_N$$

  - Calculates the rate of change of particle numbers due to sublimation process, S_N

$$S_N = \frac{N S_b}{q_b}$$

  - Calculates transport rate of blowing snow

$$Q_t = \rho \int_{z_{lb}}^{z_{ub}} \vec{V} q_b dz$$

Model Description - Snow

- **Snow Processes- Snow Compaction (Anderson 1976)**

$$\frac{1}{\rho_z(z)}\frac{d\rho_z(z)}{dt} = C_1 W_s(z) e^{0.08T_s(z) - C_2\rho_z(z)}$$

- **Snow Processes- Snow Albedo**
  - Snow surface albedo parameterization takes into account snow grain size, solar zenith angle, snow impurities, cloud optical depth, and clear sky correction (Gardner and Sharp 2010; Munneke et al. 2011).

$\alpha = \alpha_s + d\alpha_{cos\theta_0} + d\alpha_c + d\alpha_\tau + d\alpha_h.$

$$\alpha_s = 1.48 - .127048 r_e^{0.07}$$

$$d\alpha_{cos\theta_0} = 0.53\alpha_s(1-\alpha_s)(1-0.64x-(1-x)cos\theta_0)^{1.2}$$

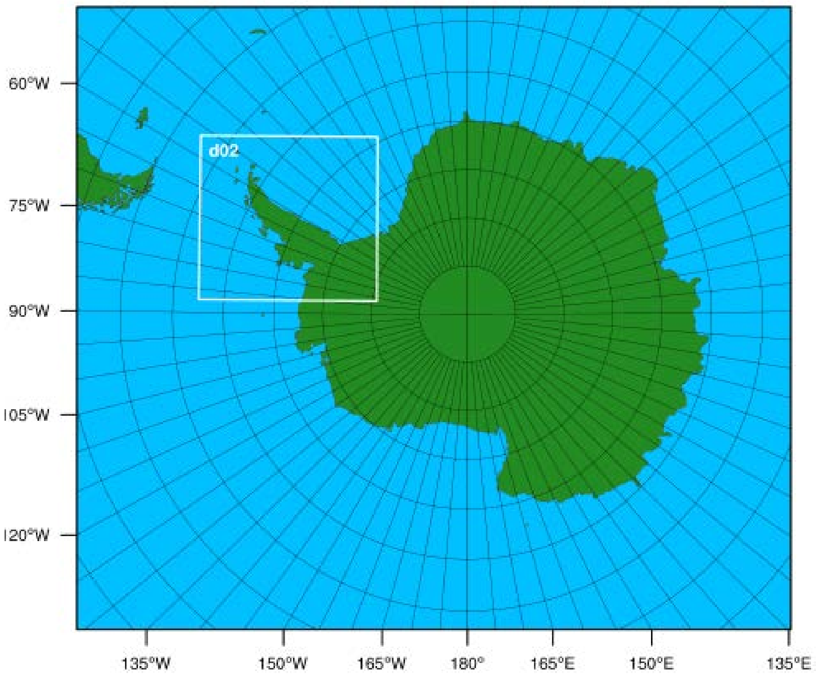
$$d\alpha_c = 0$$

$$d\alpha_\tau = \frac{0.1\tau\alpha_s^{1.3}}{(1+1.5\tau)^{\alpha_s}}$$

$$d\alpha_h = 0.03247\ln\left(\frac{p}{1538.8}\right)$$

$$x = \min(\sqrt{\tau/3cos\theta_0}, 1)$$

WRF model



- WRF version 3.6.1
- Dimensions
  - 161x141 (50km res)
  - 161x149 (12.5 km res)
  - 49 vertical levels
- Physic Schemes:
  - Microphysics – Morrison 2-moment
  - Longwave – RRTMG
  - Shortwave – RRTMG
  - Sfclay – MM5 Similarity
  - Surface – Noah LSM + Ice sheet + sea ice+ bsnow
  - Cumulus – Kain-Fritsch
  - PBL – MYNN + bsnow
- Initialization and forcing with CCSM4 CMIP5 simulation
- Run for the entire month of December 2005

Model testing

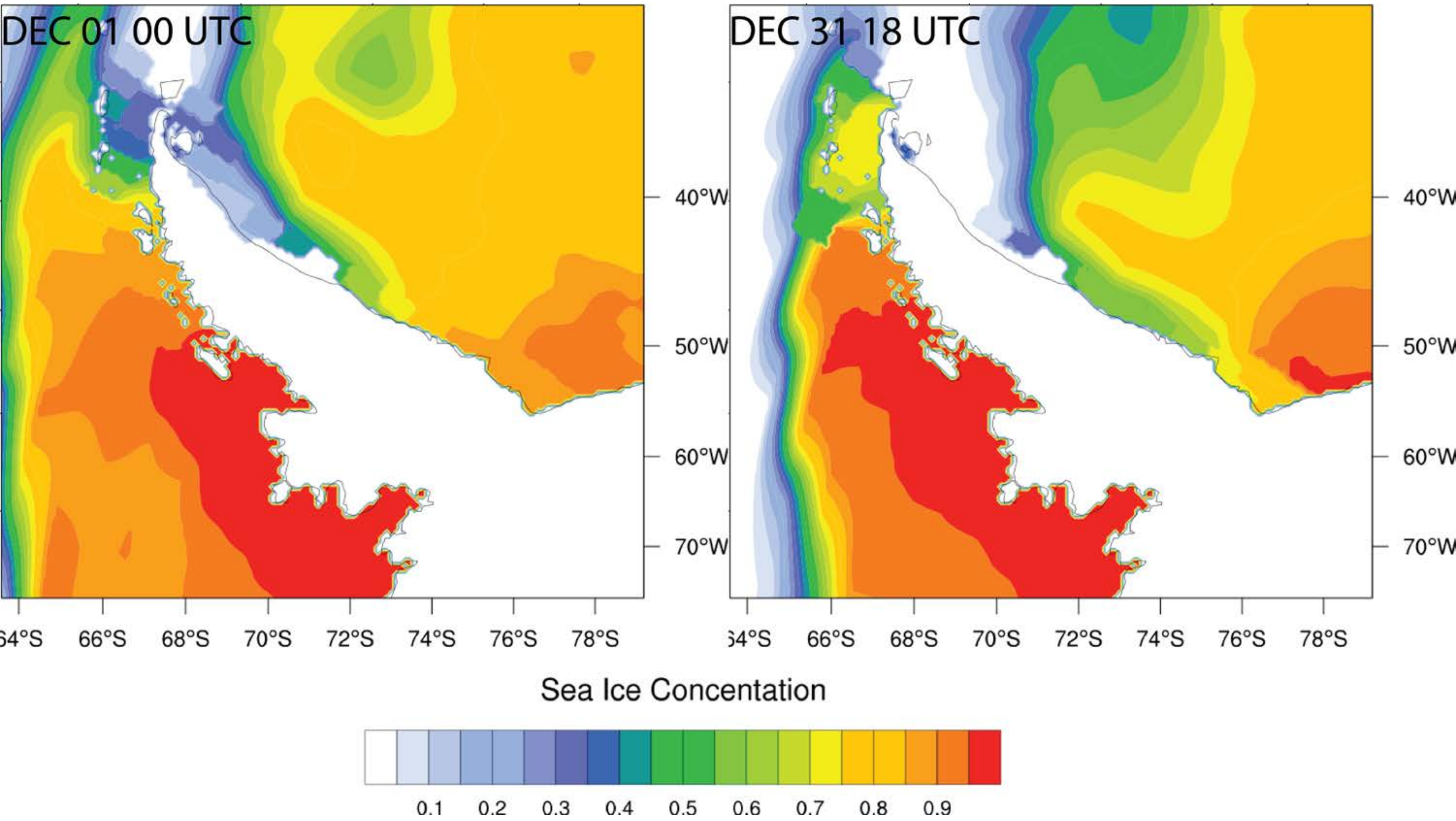
- Test sensitivity to blowing snow processes and albedo changes

Experiment	Blowing Snow	Albedo
WRF-ice	On	Gardner and Sharp (2010)
WRF-ice/wout bsnow	Off	Gardner and Sharp (2010)
WRF-ice/const. alb.	On	0.85
WRF-ice/wout bsnow/const. alb.	Off	0.85

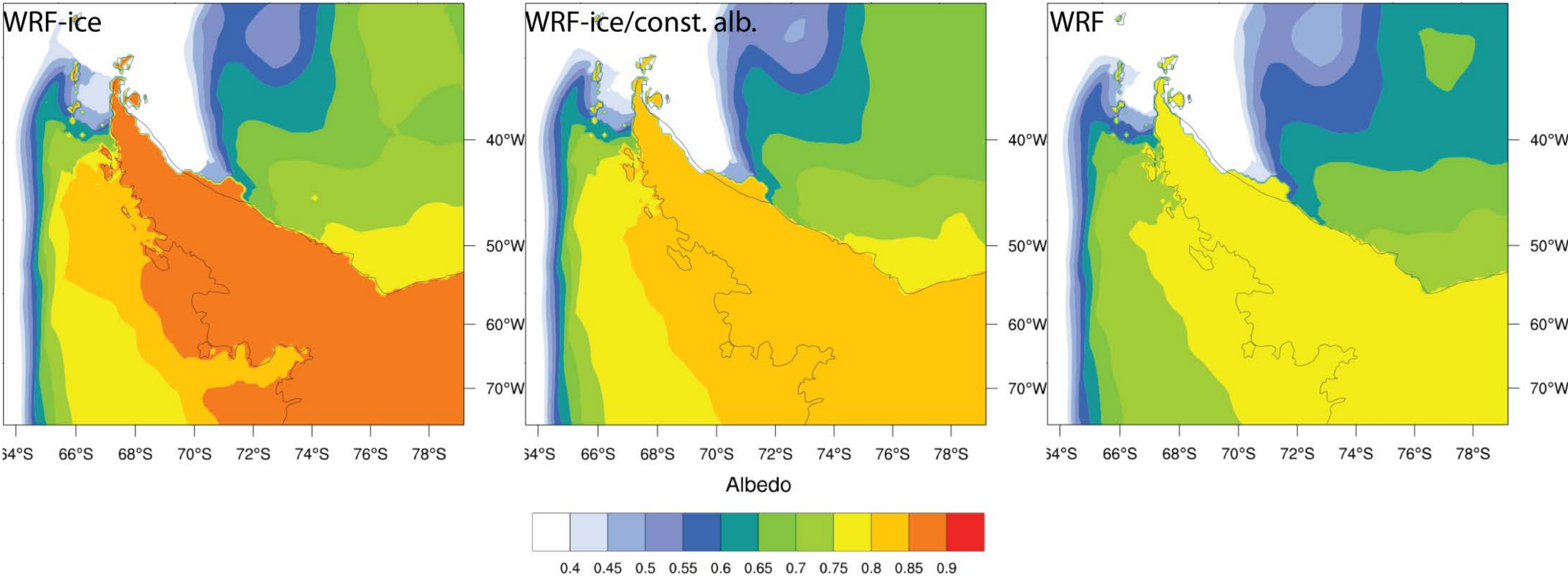
- WRF is also ran without any of the modifications (out of the box) for comparison.

Preliminary Results

Sea ice Concentration

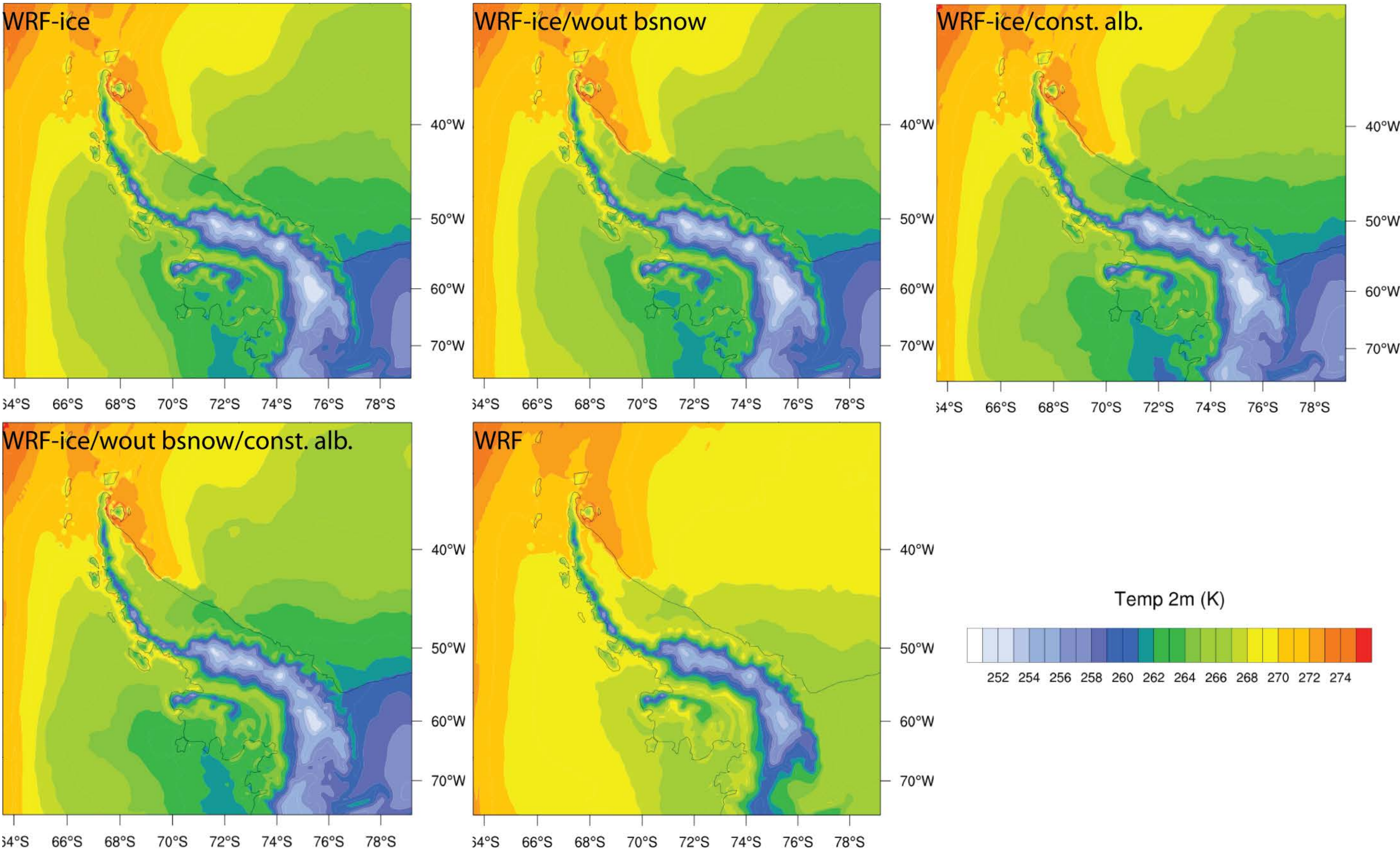


Albedo

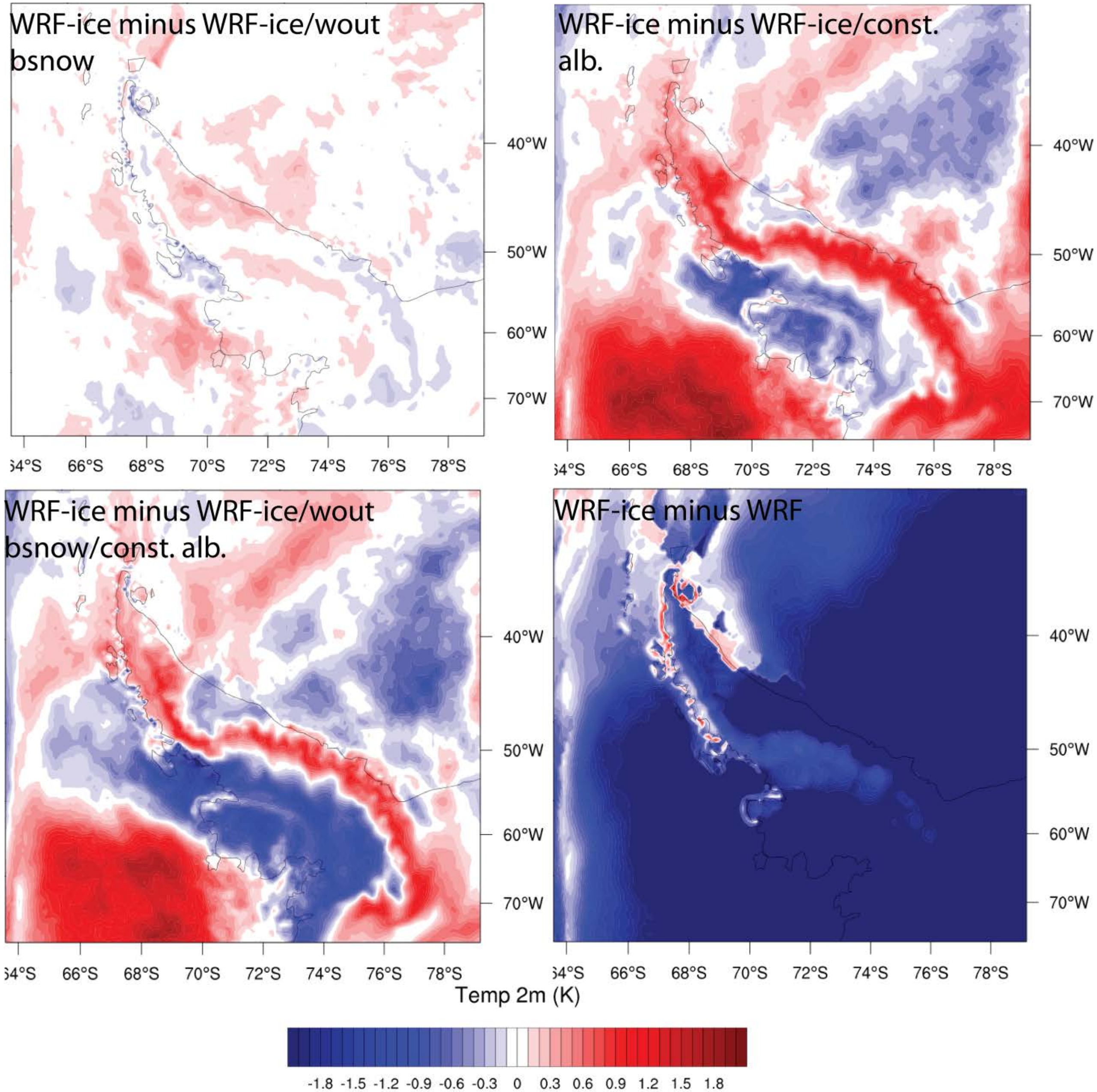


WRF-ice
WRF-ice/const. alb.
WRF
40°W
50°W
60°W
70°W
66°S
68°S
70°S
72°S
74°S
76°S
78°S
Albedo
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9

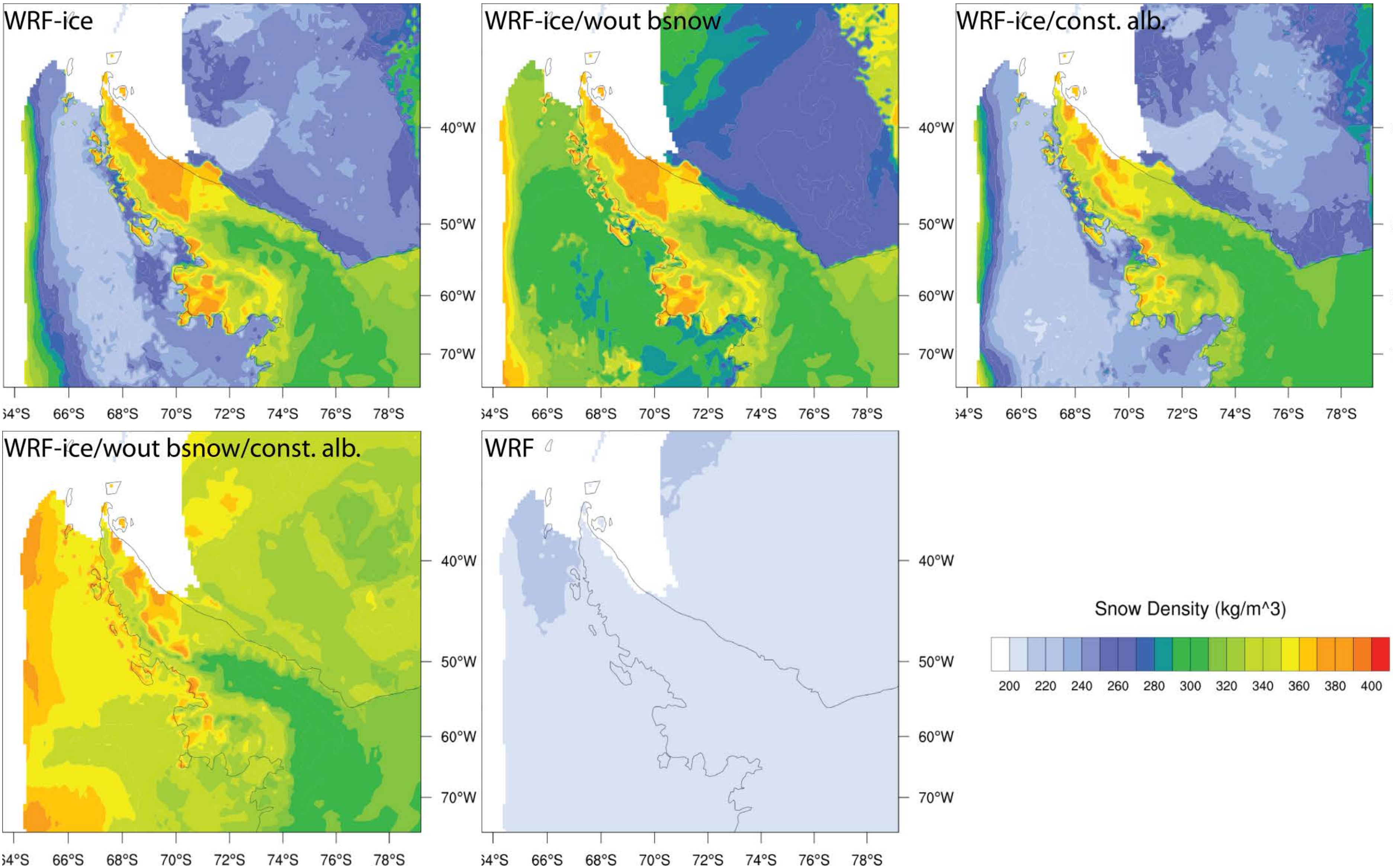
2m Temperature



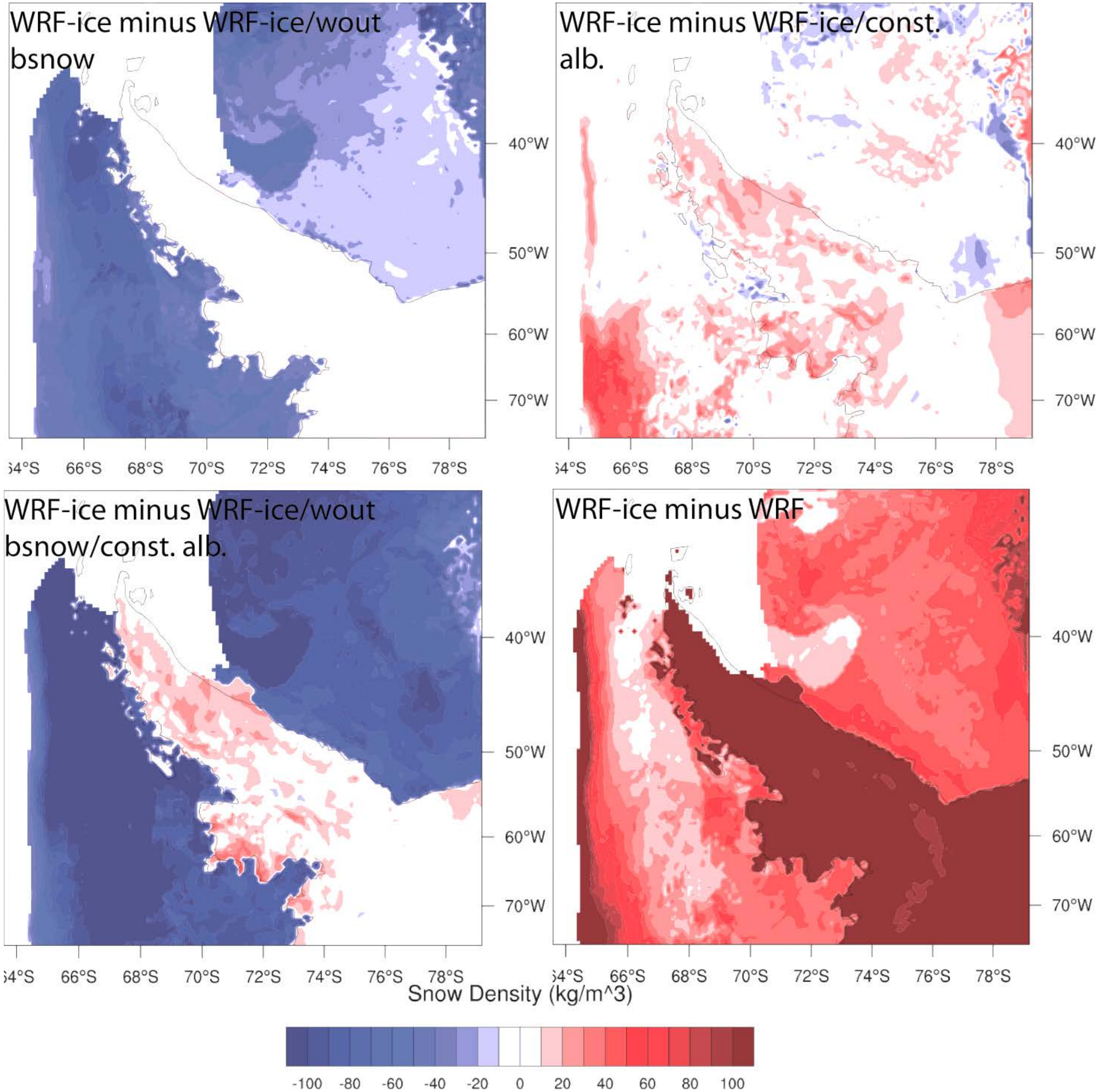
2m Temperature



Snow Density



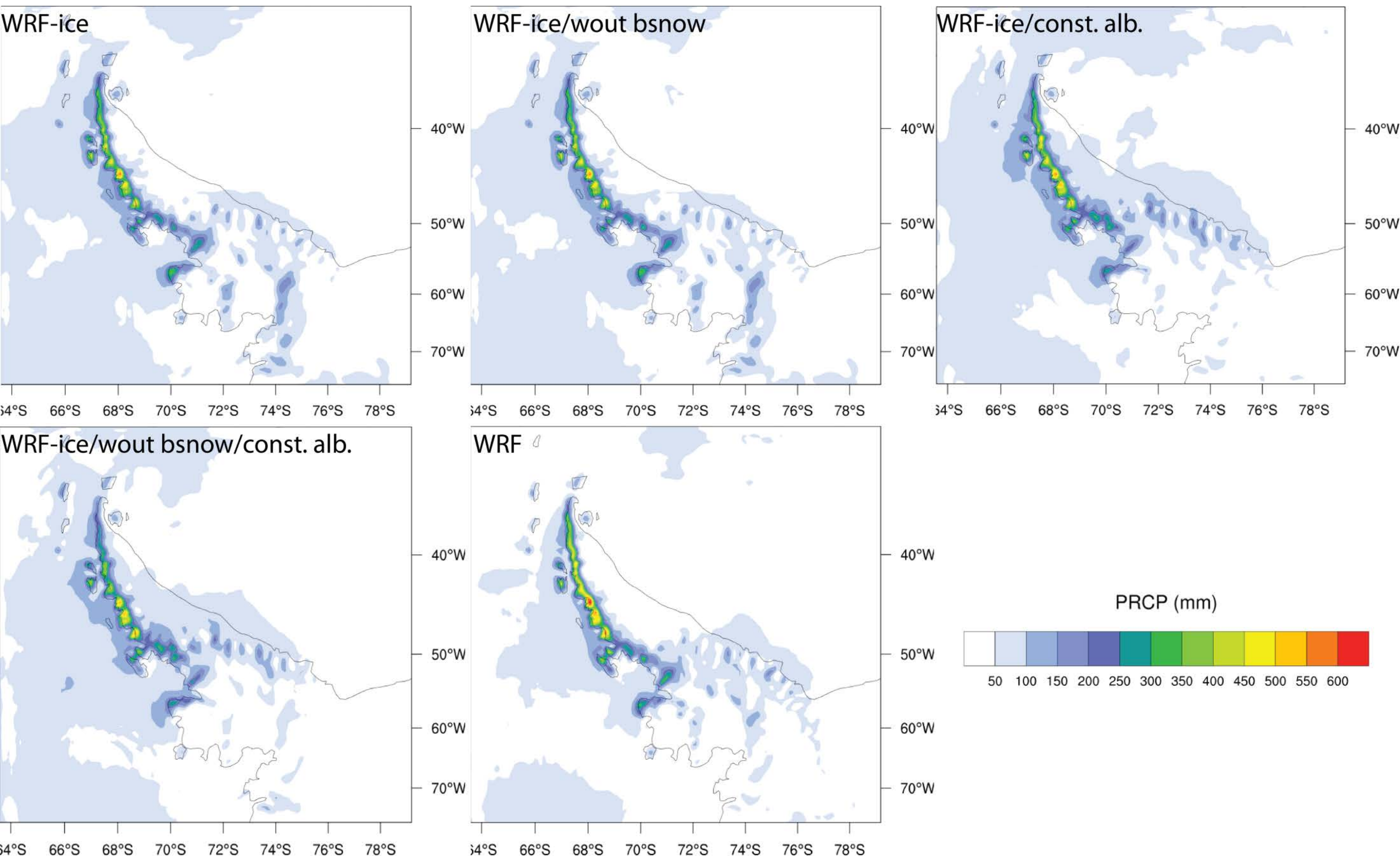
Snow Density



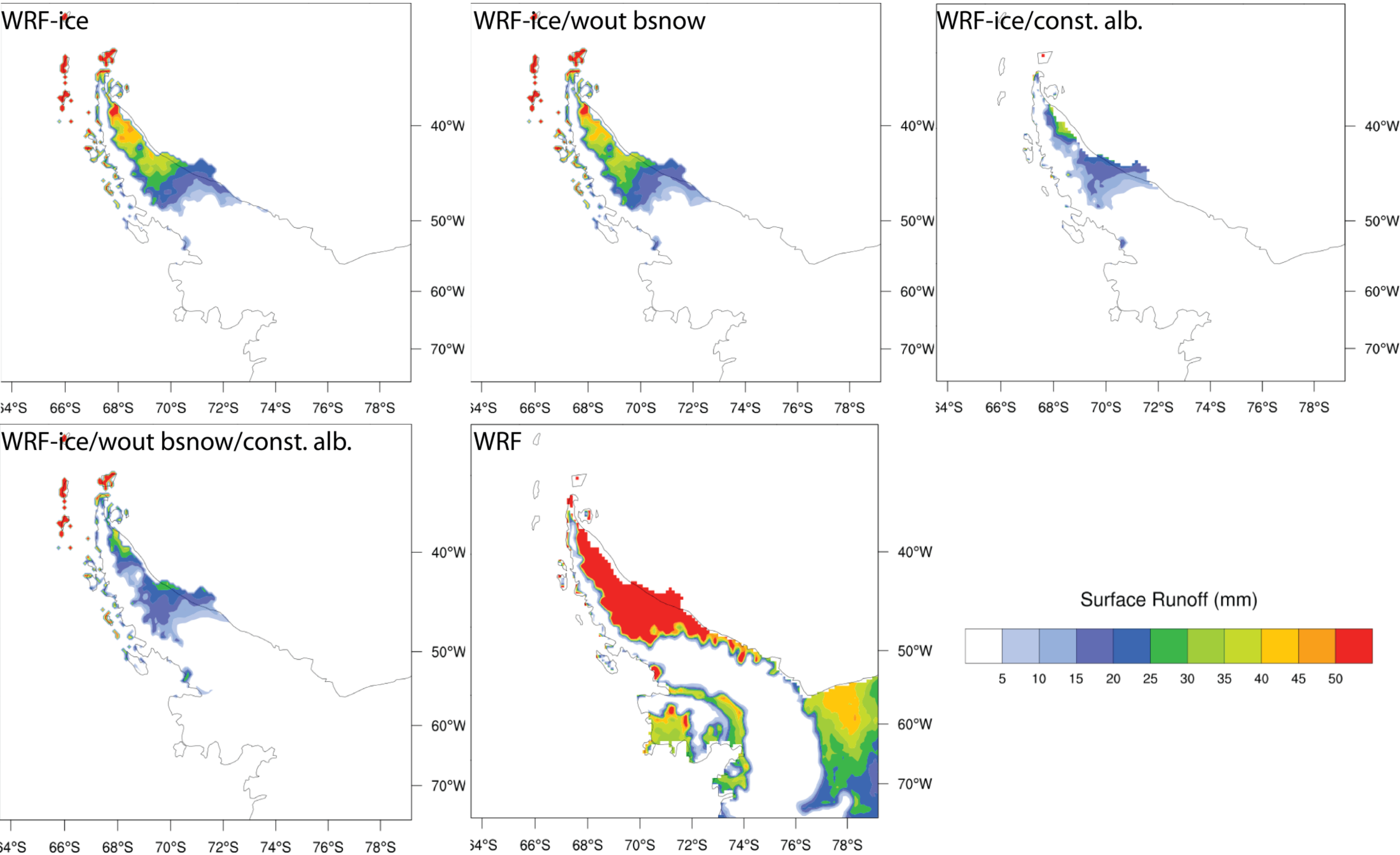
Surface Mass Balance

- $SMB = \int PR - RU - SU_s - SU_{ds} - ER_{ds} dt$
  - PR = Precipitation
  - RU = Runoff
  - SU_s = Surface Sublimation
  - SU_{ds} = Sublimation due to blowing snow
  - ER_{ds} = Erosion due to blowing snow

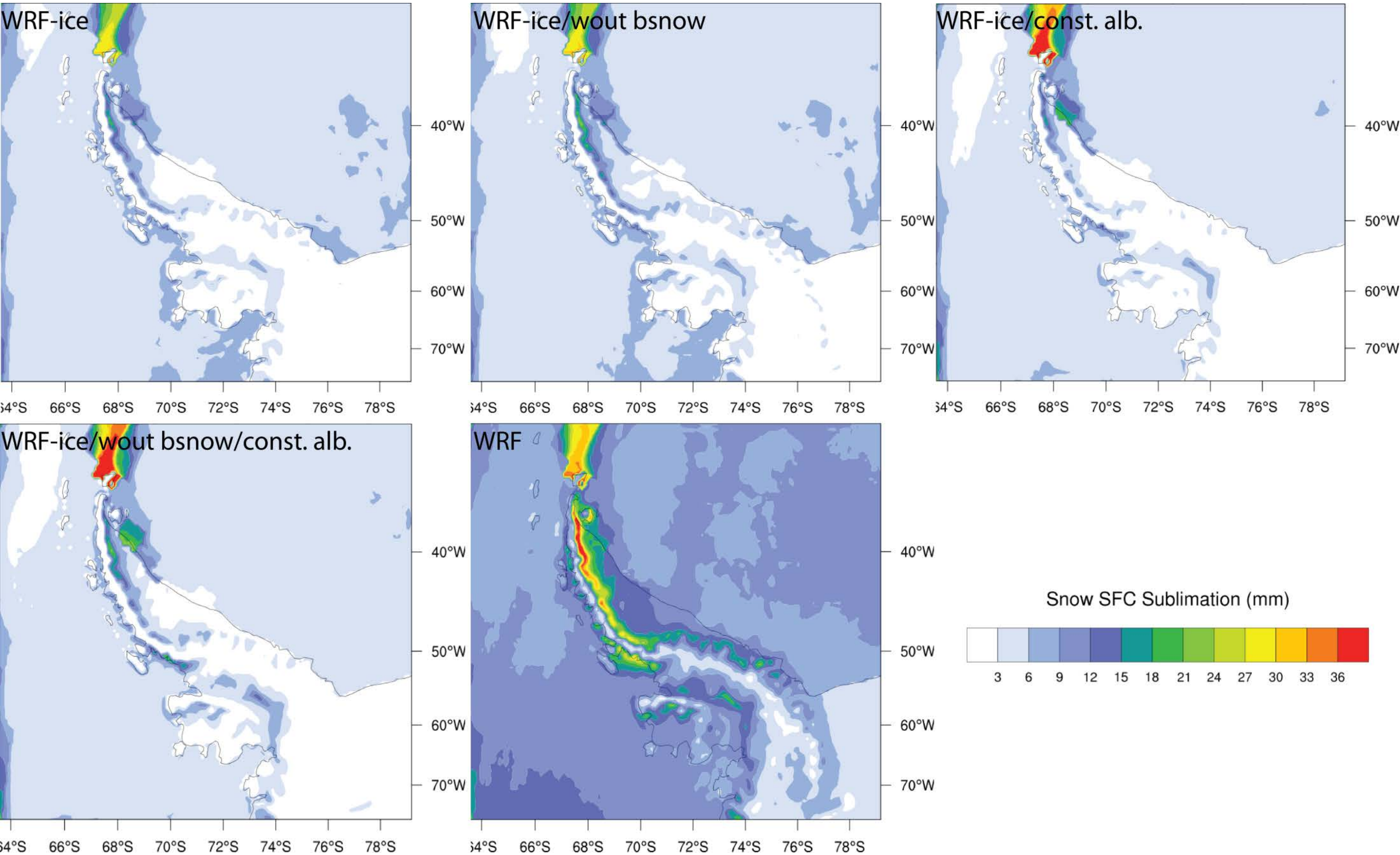
Precipitation



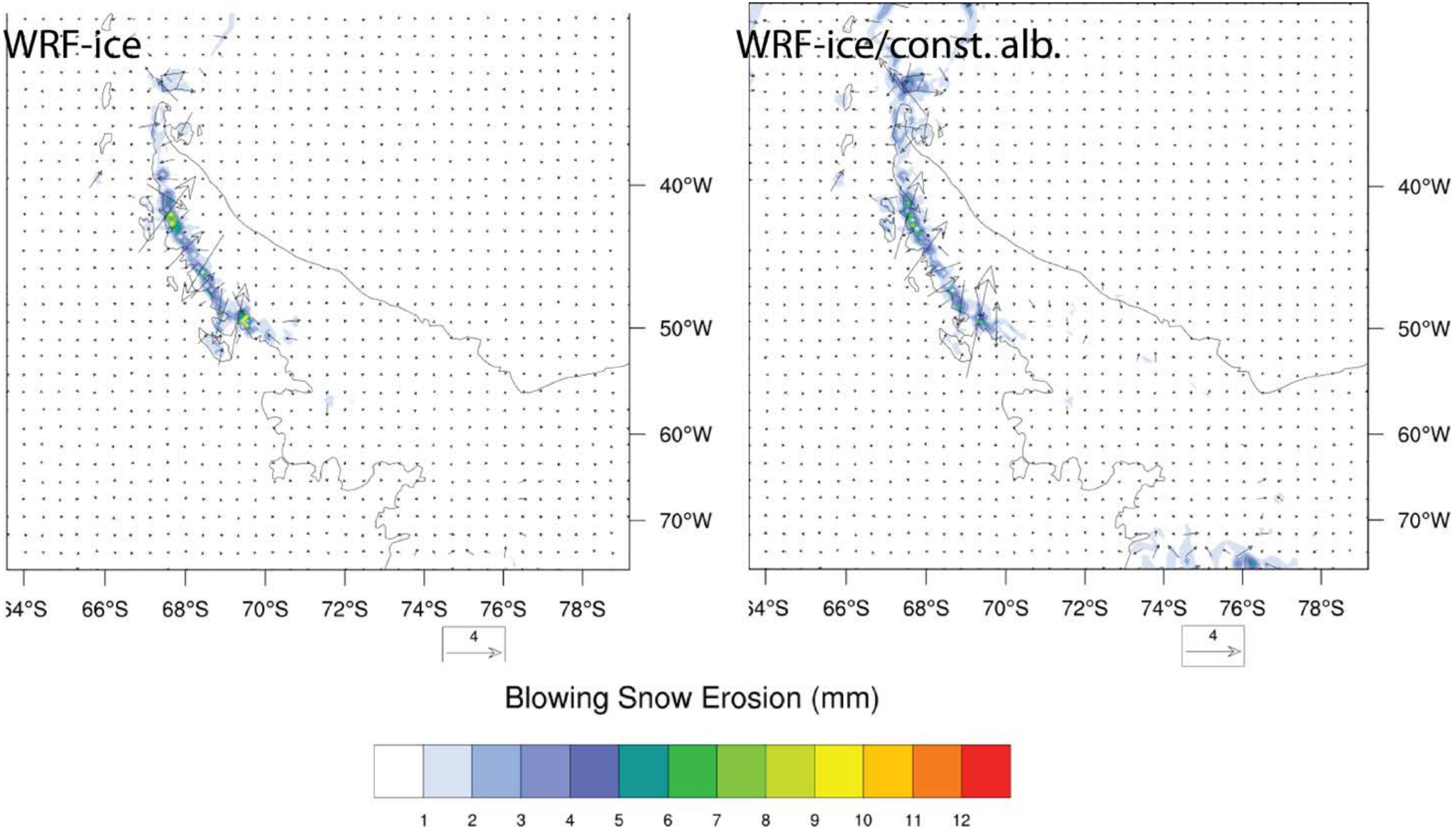
Runoff


WRF-ice
WRF-ice/wout bsnow
WRF-ice/const. alb.
WRF-ice/wout bsnow/const. alb.
WRF
40°W
50°W
60°W
70°W
66°S
68°S
70°S
72°S
74°S
76°S
78°S
Surface Runoff (mm)
5
10
15
20
25
30
35
40
45
50

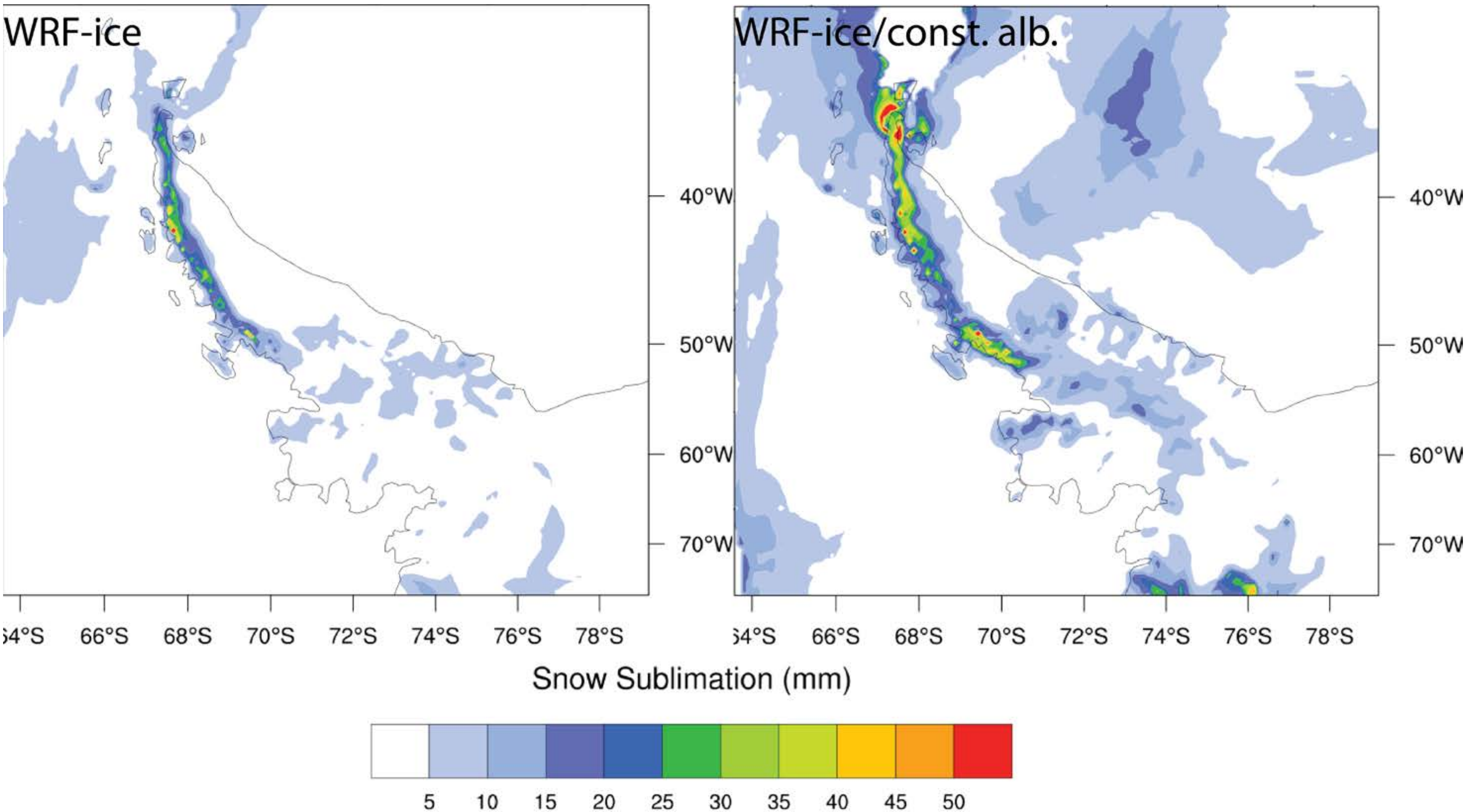
Surface Sublimation



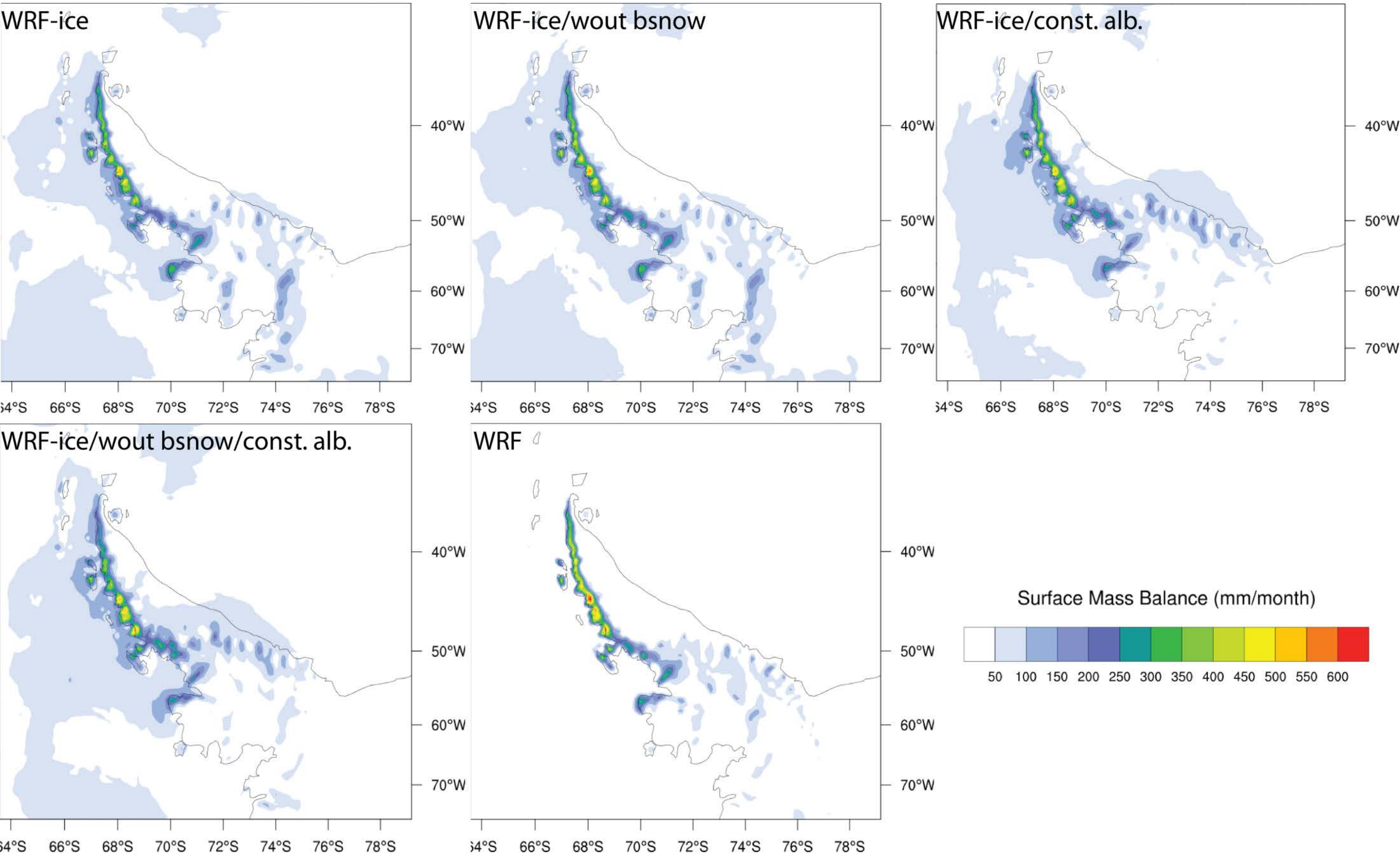
Blowing Snow Erosion



Blowing Snow Sublimation



Surface Mass Balance

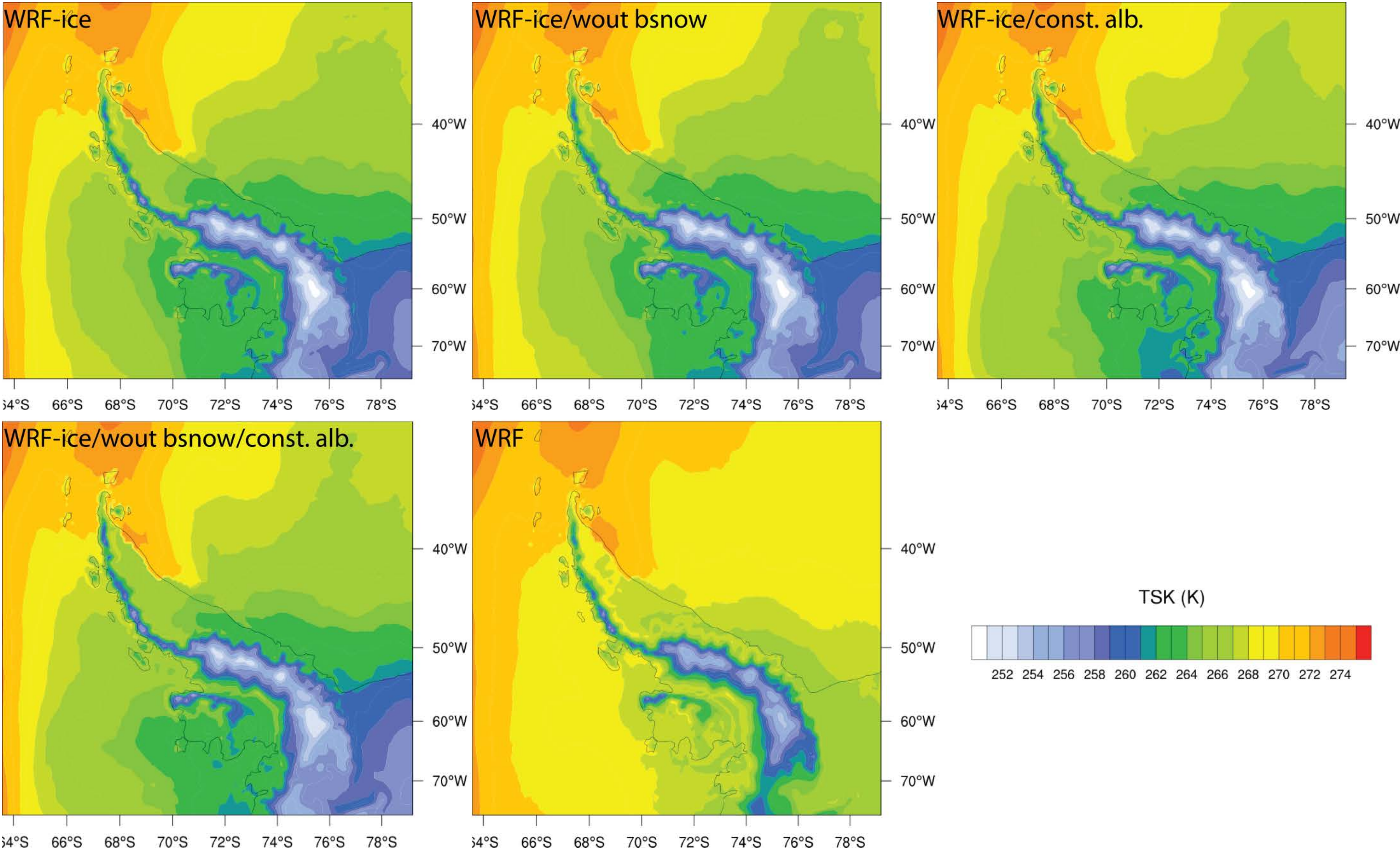


Summary

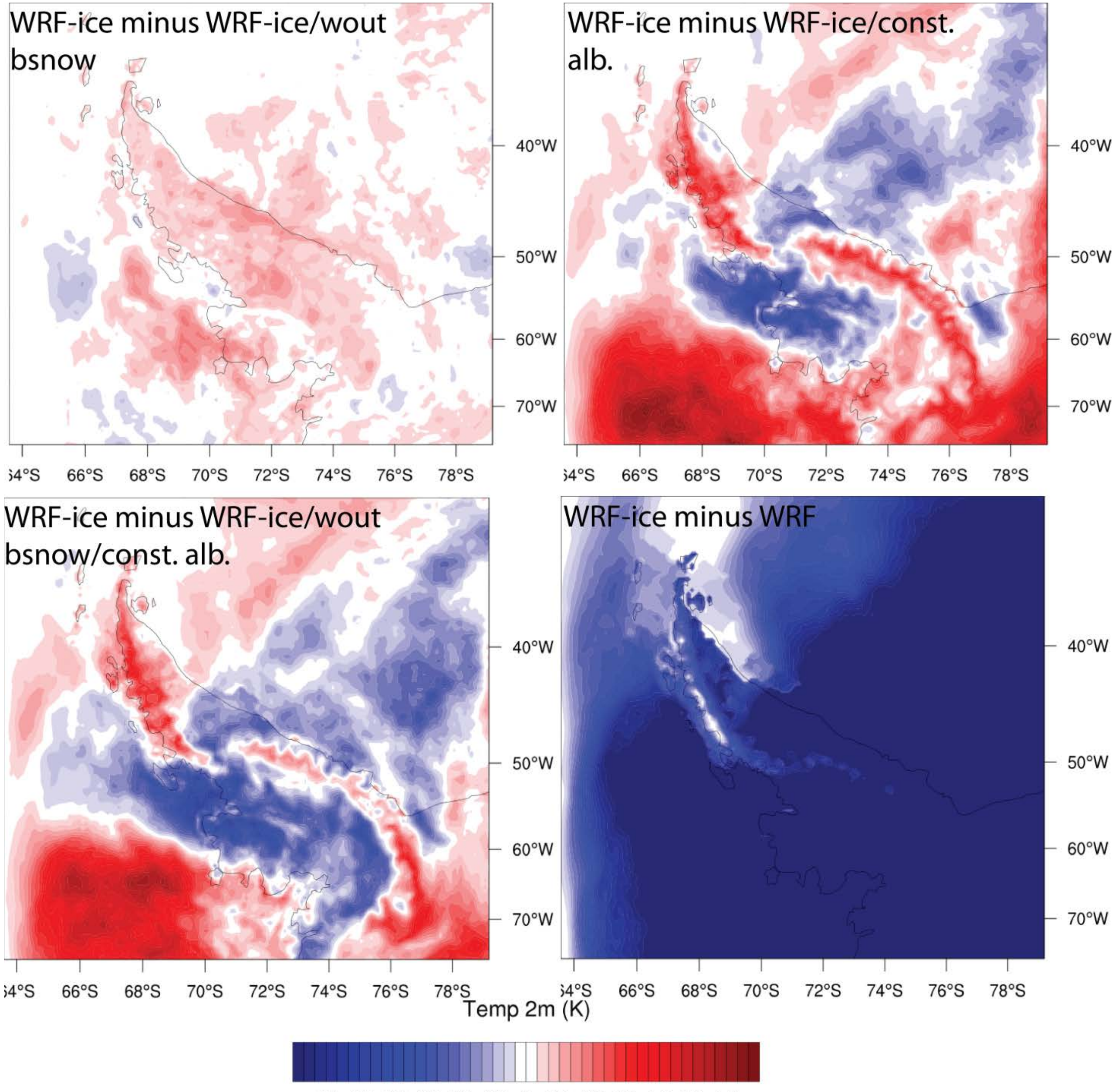
- WRF-ice modules has been successfully implemented into WRF.
- Model runs well for the period tested.
- More sensitivity testing for longer period including different seasons are needed.
- Look for observations to further evaluate model performance.

Appendix

TSK

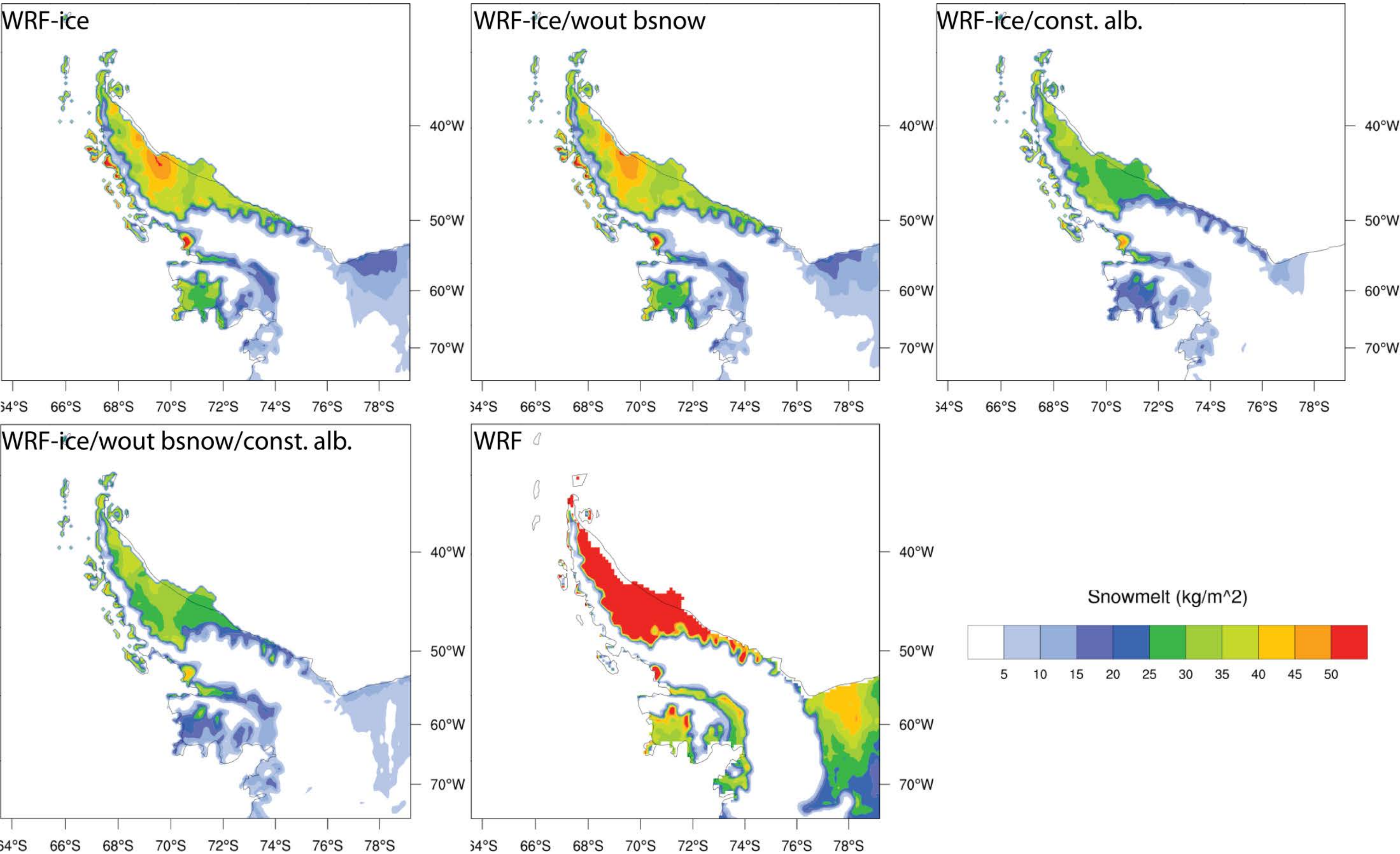

WRF-ice
WRF-ice/wout bsnow
WRF-ice/const. alb.
WRF-ice/wout bsnow/const. alb.
WRF
40°W
50°W
60°W
70°W
66°S 68°S 70°S 72°S 74°S 76°S 78°S
TSK (K)
252 254 256 258 260 262 264 266 268 270 272 274

TSK

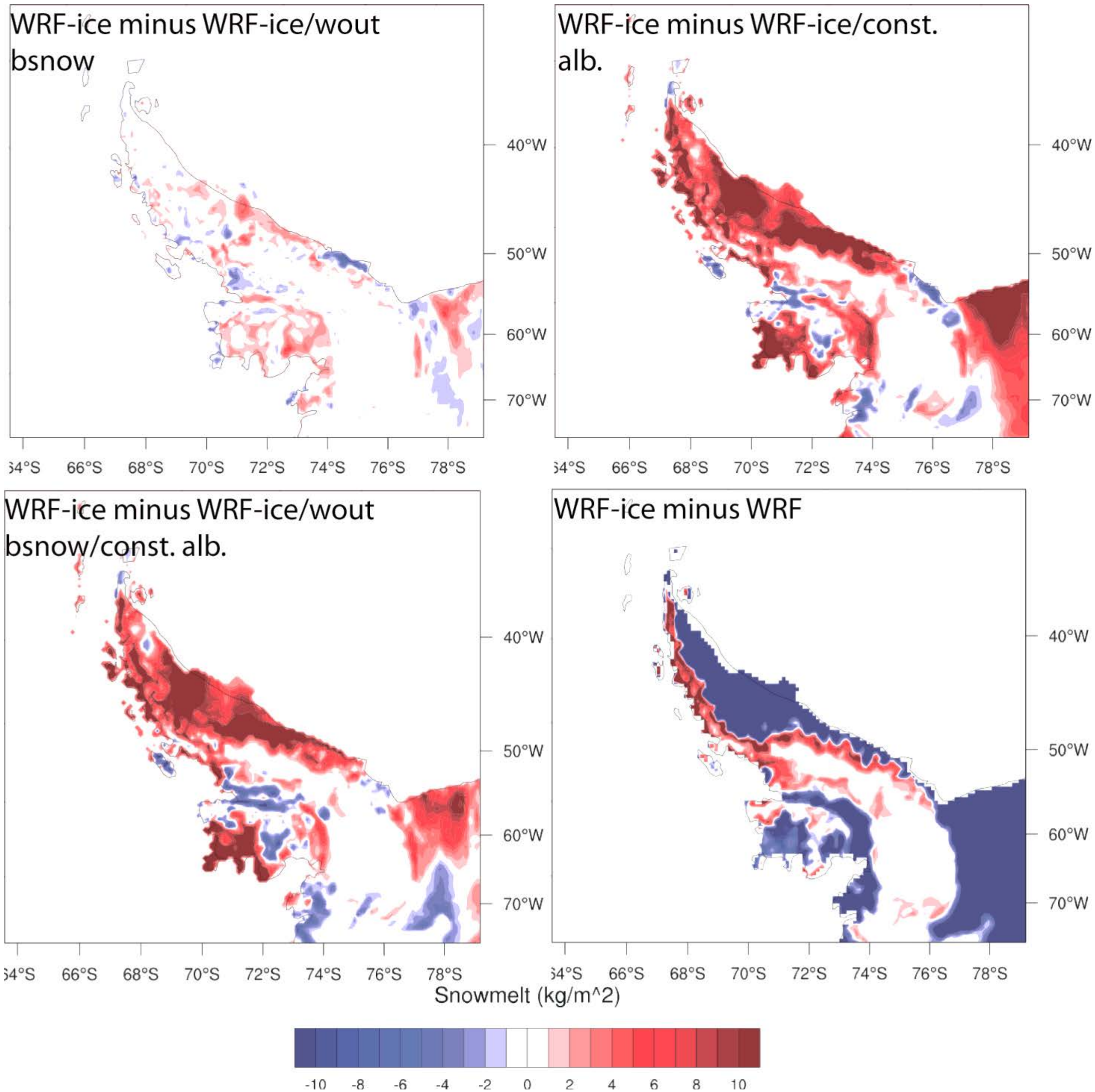


WRF-ice minus WRF-ice/wout bsnow
WRF-ice minus WRF-ice/const. alb.
WRF-ice minus WRF-ice/wout bsnow/const. alb.
WRF-ice minus WRF
40°W
50°W
60°W
70°W
64°S 66°S 68°S 70°S 72°S 74°S 76°S 78°S
Temp 2m (K)
-1.8 -1.5 -1.2 -0.9 -0.6 -0.3 0 0.3 0.6 0.9 1.2 1.5 1.8

Snowmelt

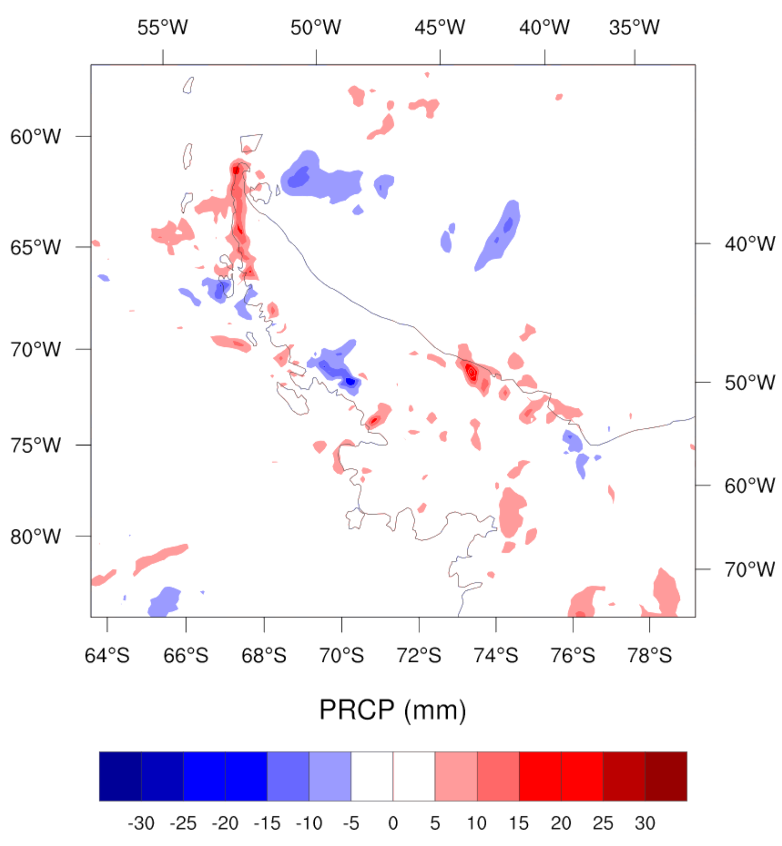

WRF-ice
WRF-ice/wout bsnow
WRF-ice/const. alb.
WRF-ice/wout bsnow/const. alb.
WRF
40°W
50°W
60°W
70°W
66°S
68°S
70°S
72°S
74°S
76°S
78°S
Snowmelt (kg/m^2)
5
10
15
20
25
30
35
40
45
50

Snowmelt

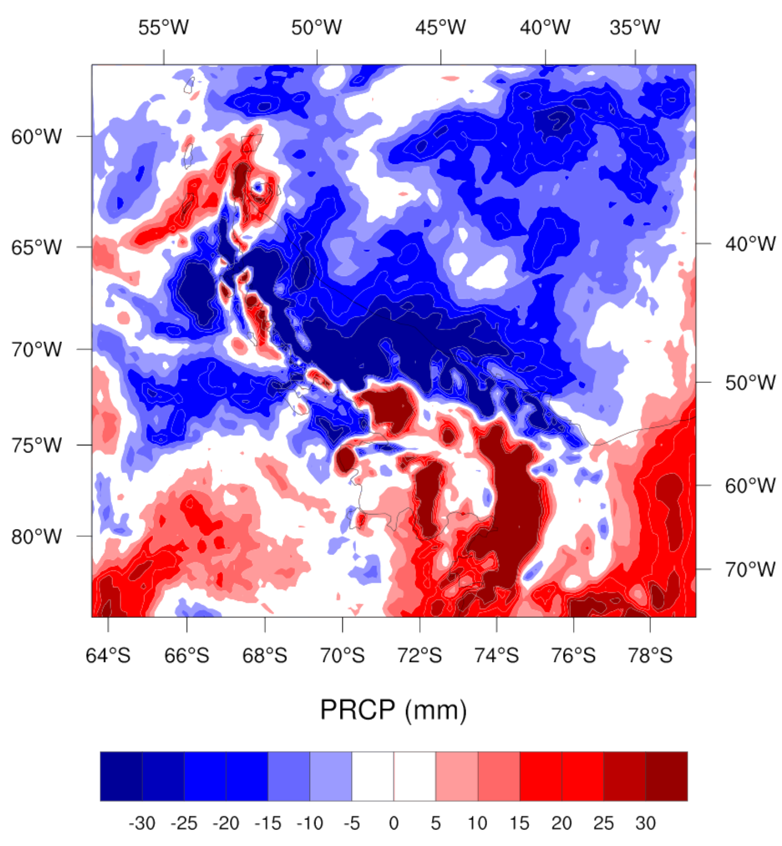

WRF-ice minus WRF-ice/wout bsnow
WRF-ice minus WRF-ice/const. alb.
WRF-ice minus WRF-ice/wout bsnow/const. alb.
WRF-ice minus WRF
40°W
50°W
60°W
70°W
66°S
68°S
70°S
72°S
74°S
76°S
78°S
Snowmelt (kg/m^2)
-10
-8
-6
-4
-2
0
2
4
6
8
10

Precipitation-Differences

WRF-ice minus WRF-ice/wout blowing snow

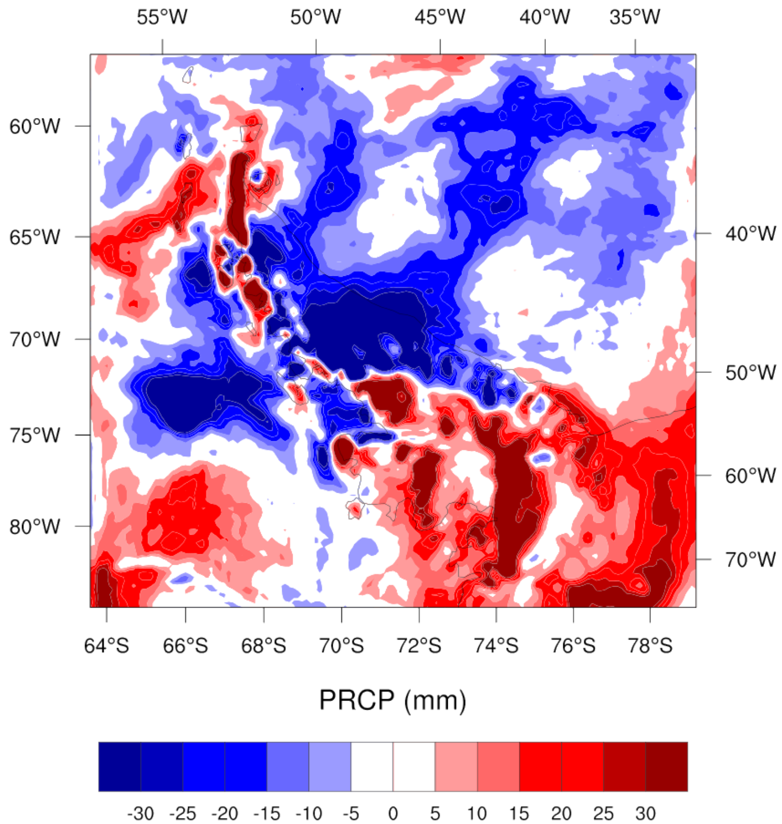


WRF-ice minus WRF-ice/ constant albedo

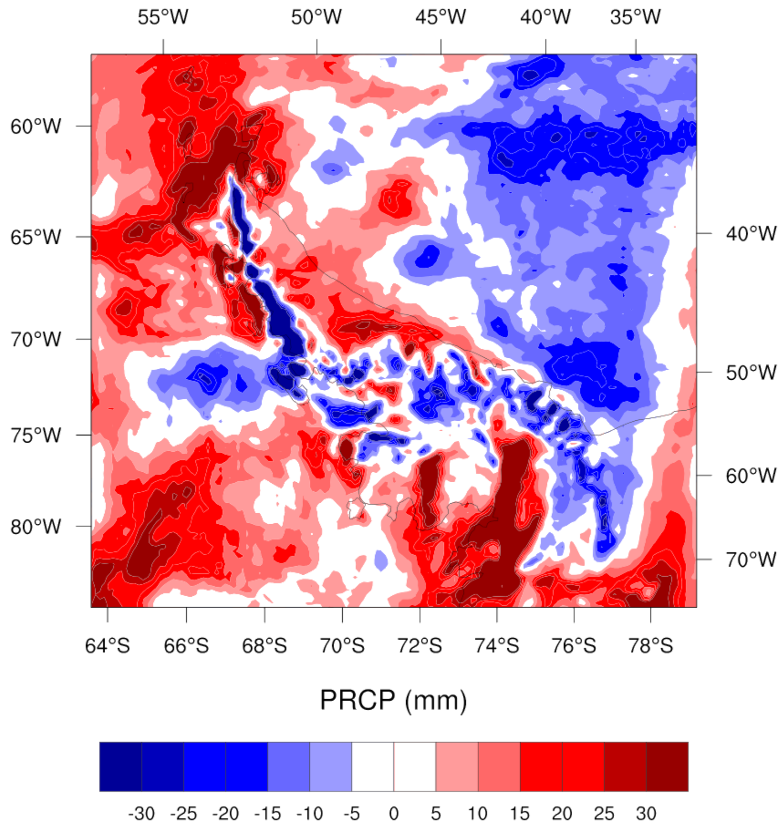


Precipitation-Differences

WRF-ice minus WRF-ice/wout blowing snow/constant albedo

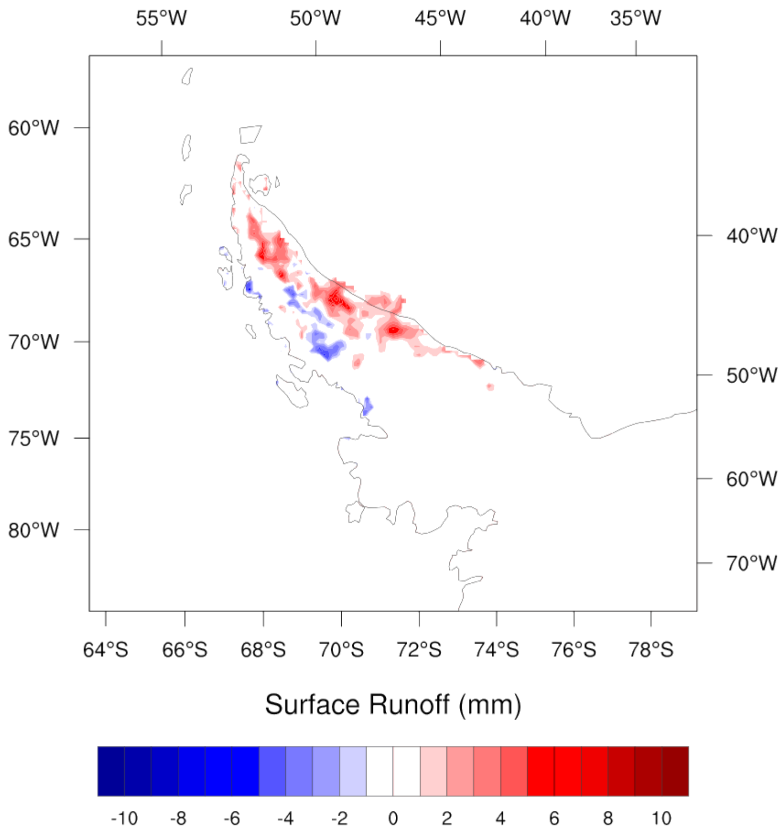


WRF-ice minus WRF

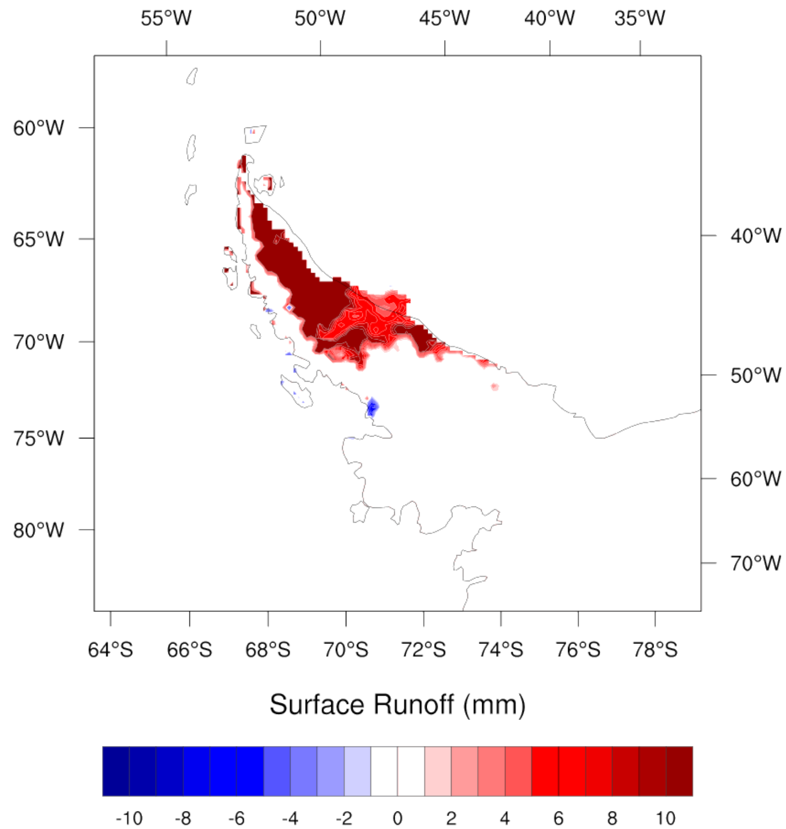


Runoff-Differences

WRF-ice minus WRF-ice/wout blowing snow

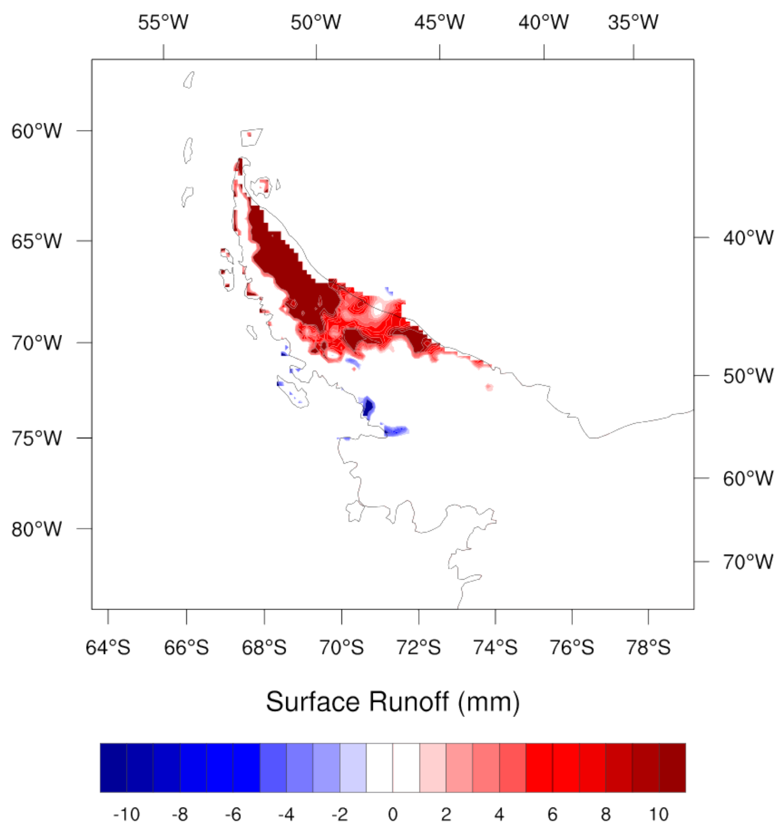


WRF-ice minus WRF-ice/ constant albedo

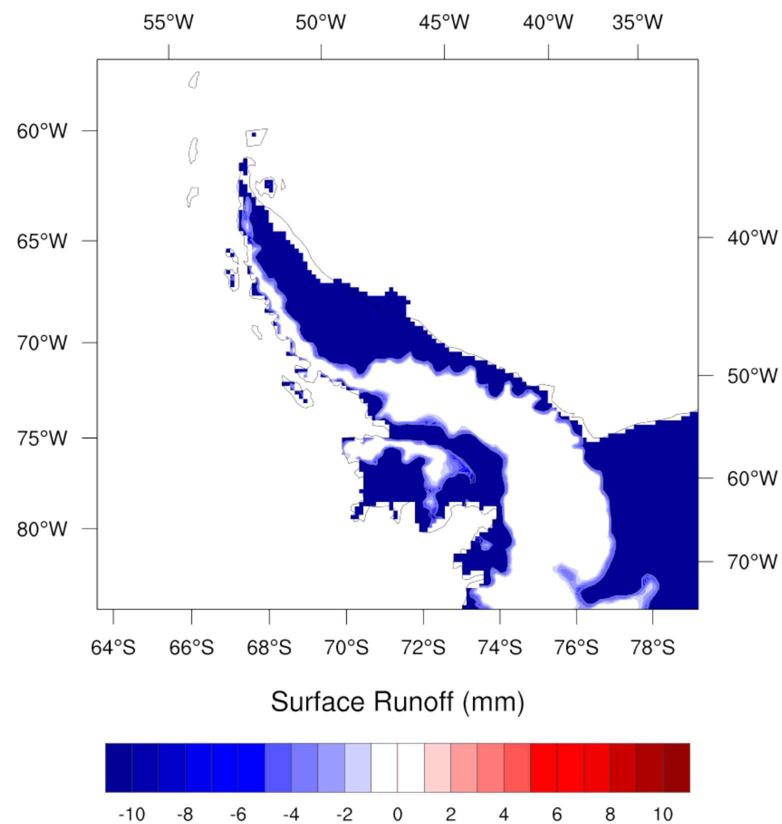


Runoff-Differences

WRF-ice minus WRF-ice/wout blowing snow/constant albedo

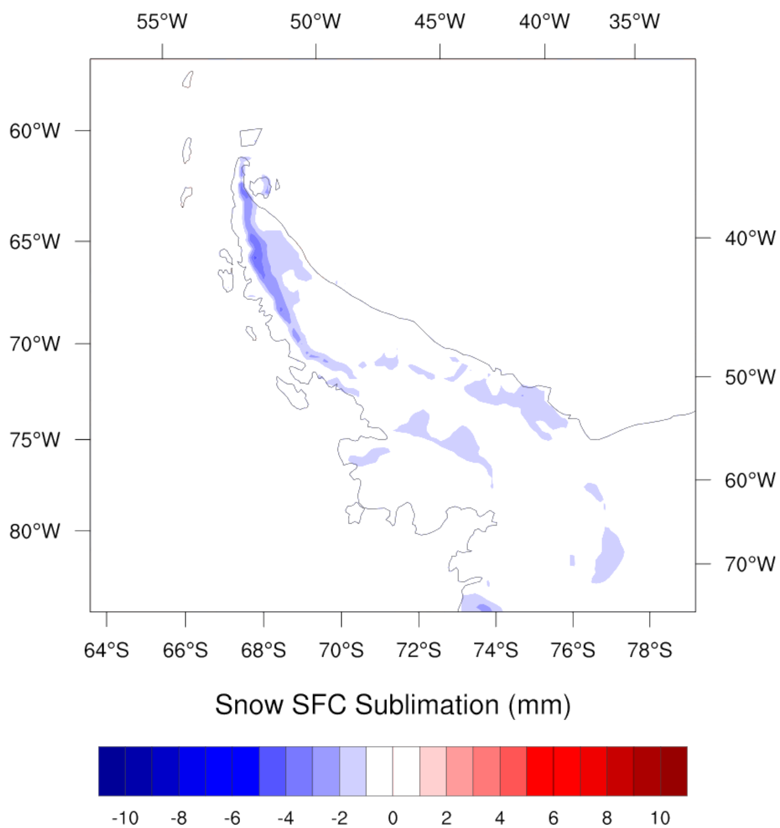


WRF-ice minus WRF

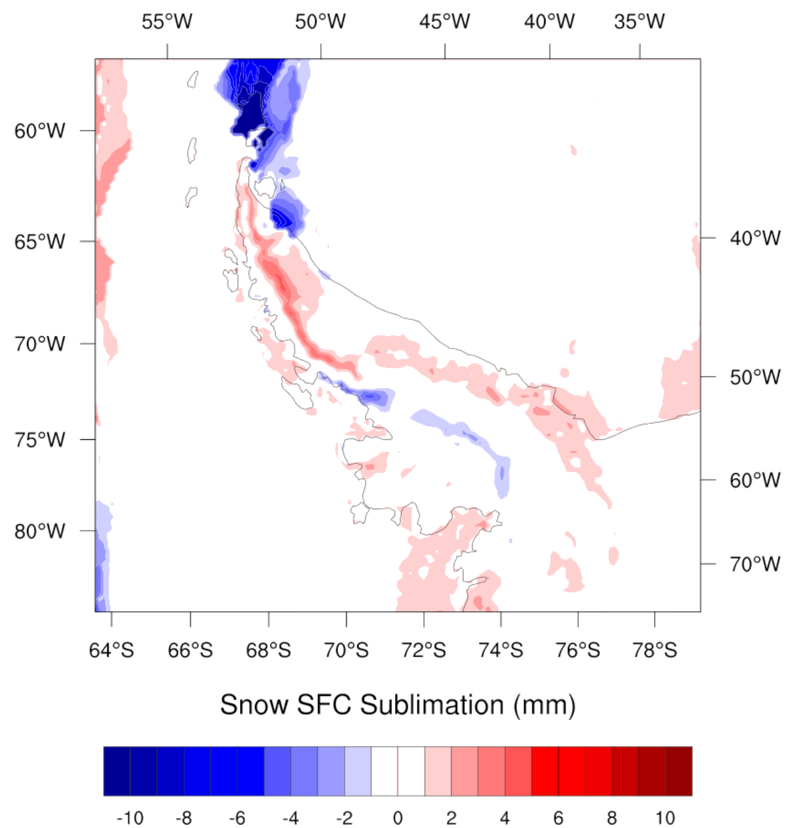


Surface Sublimation-Differences

WRF-ice minus WRF-ice/wout blowing snow

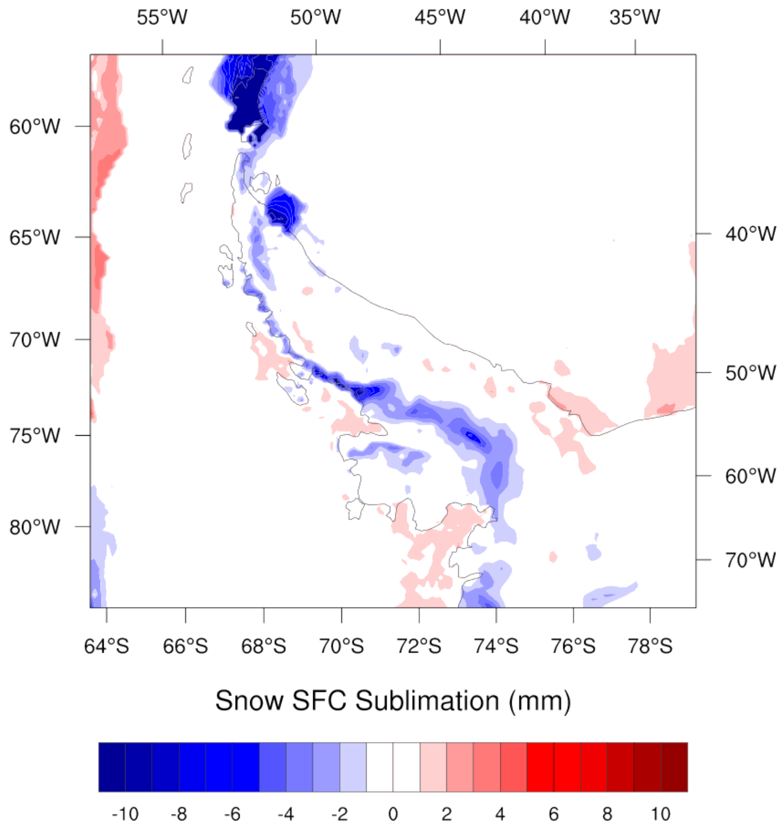


WRF-ice minus WRF-ice/ constant albedo

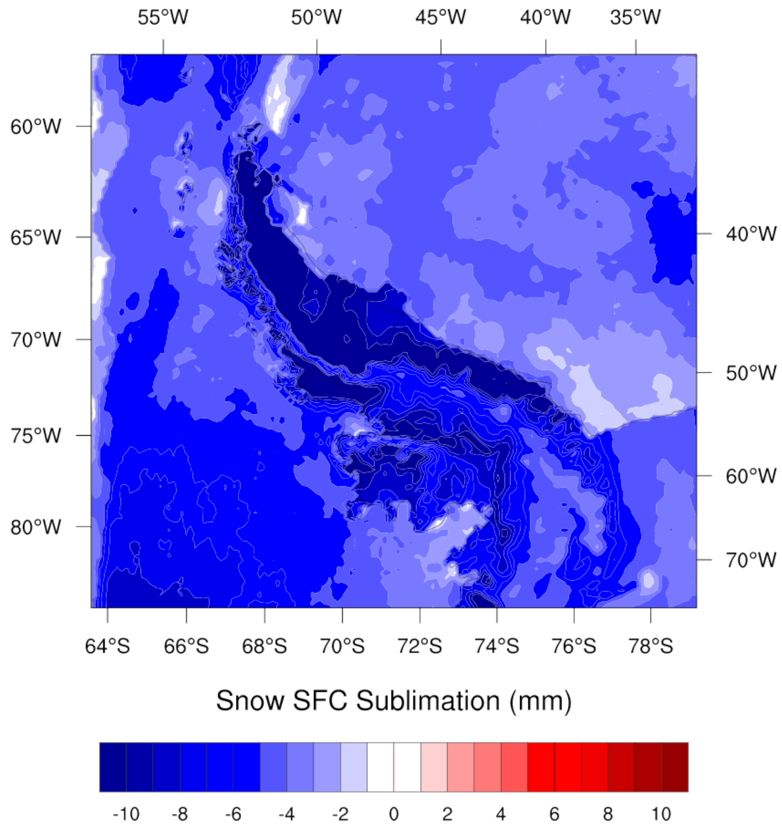


Surface Sublimation-Differences

WRF-ice minus WRF-ice/wout blowing snow/constant albedo

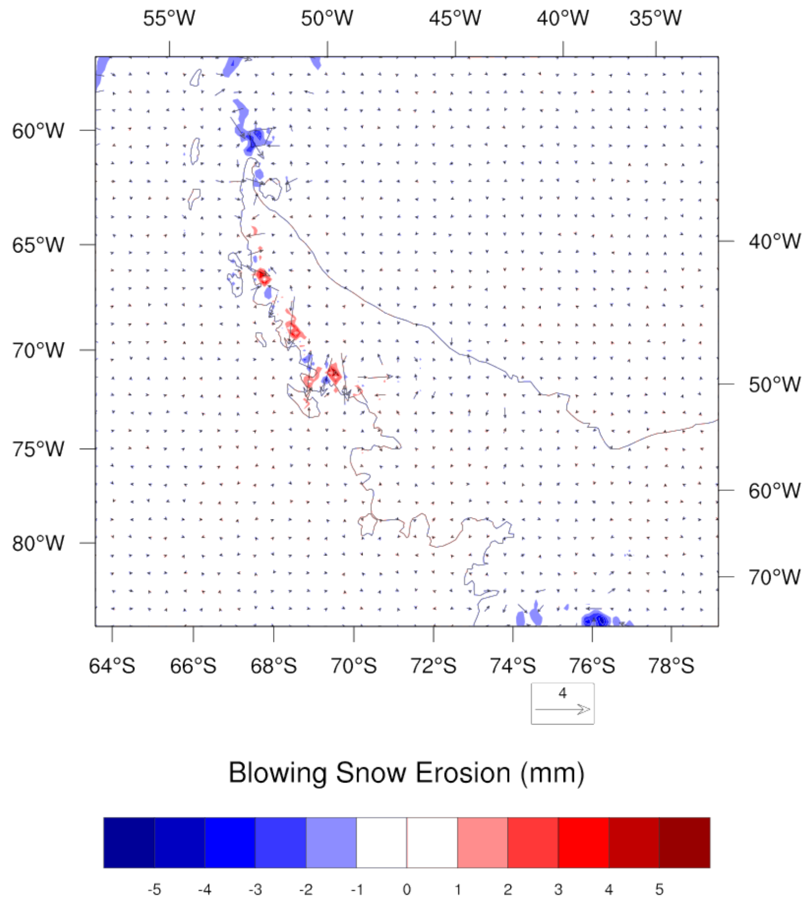


WRF-ice minus WRF



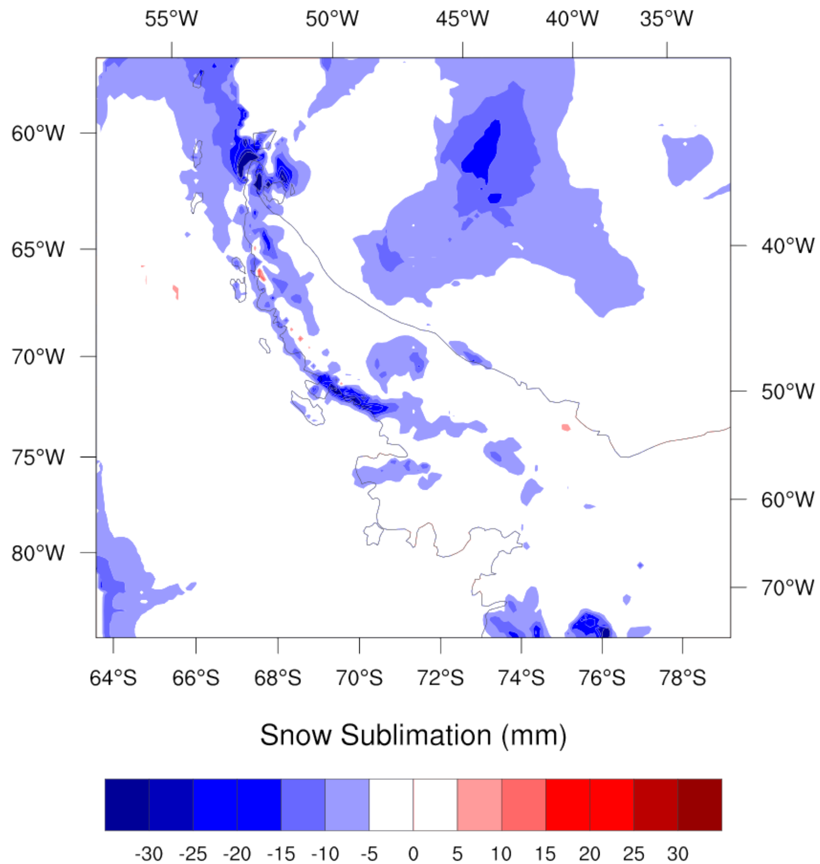
Erosion - Differences

WRF-ice minus WRF-ice/constant albedo



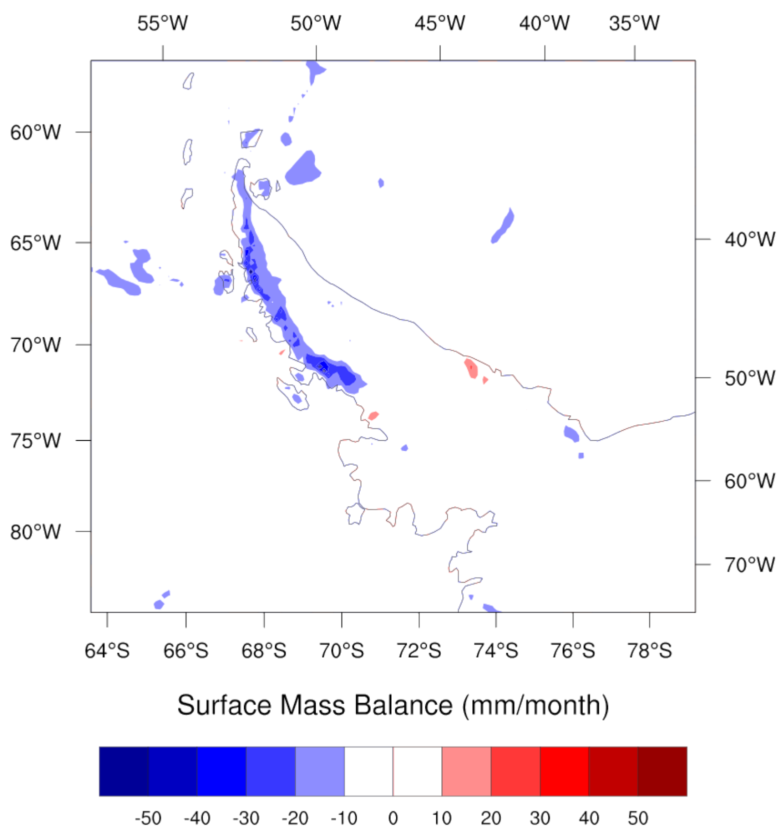
Blowing Snow Sublimation - Differences

WRF-ice minus WRF-ice/constant albedo

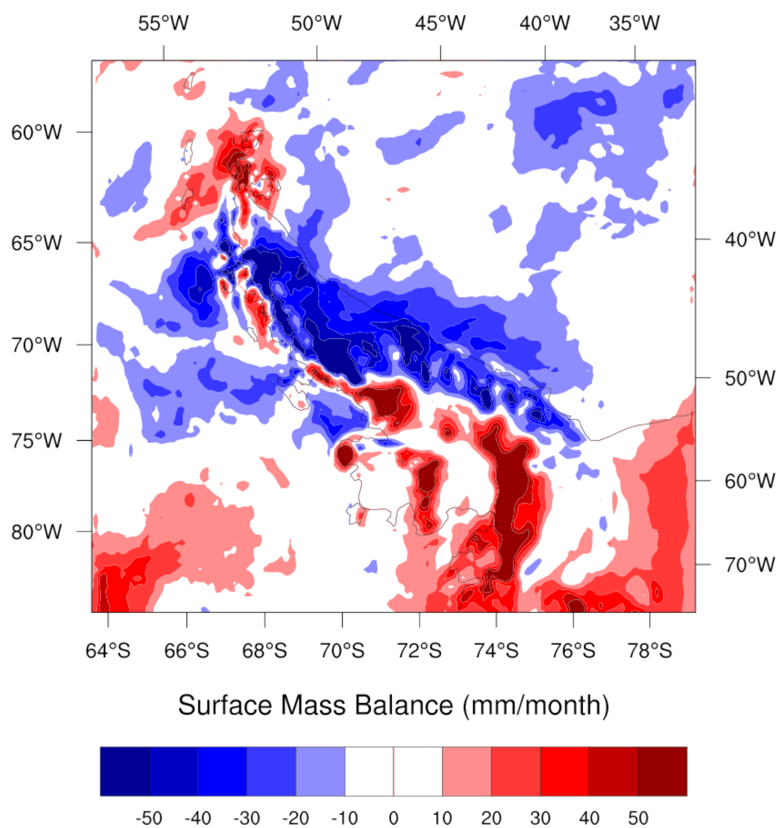


Surface Mass Balance - Differences

WRF-ice minus WRF-ice/wout blowing snow

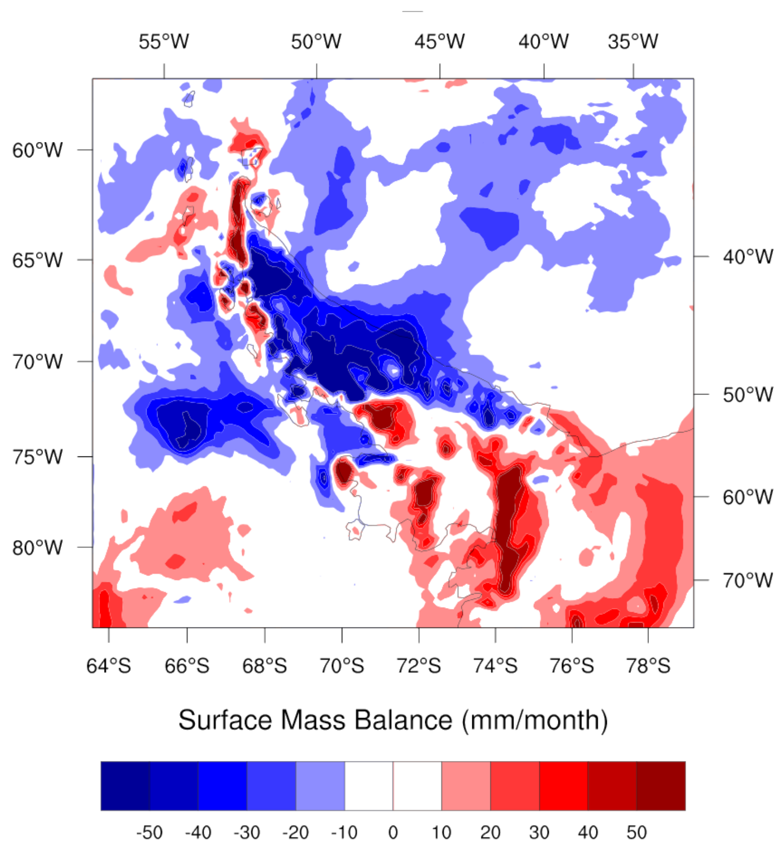


WRF-ice minus WRF-ice/ constant albedo



Surface Mass Balance - Differences

WRF-ice minus WRF-ice/wout blowing snow/constant albedo



WRF-ice minus WRF