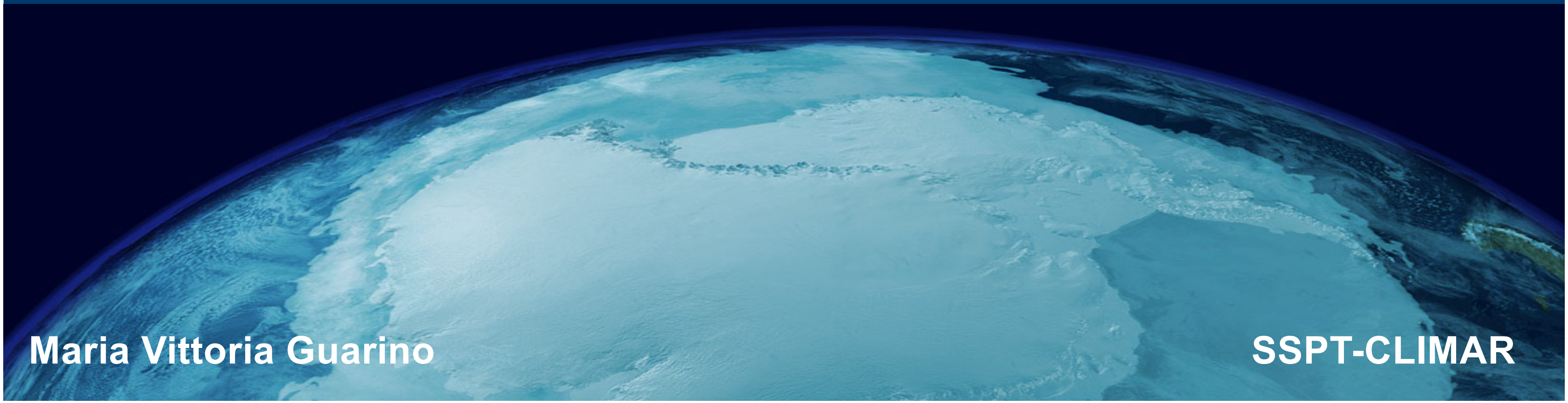
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

Southern Hemisphere sea ice response to different flow regimes over the Antarctic Peninsula

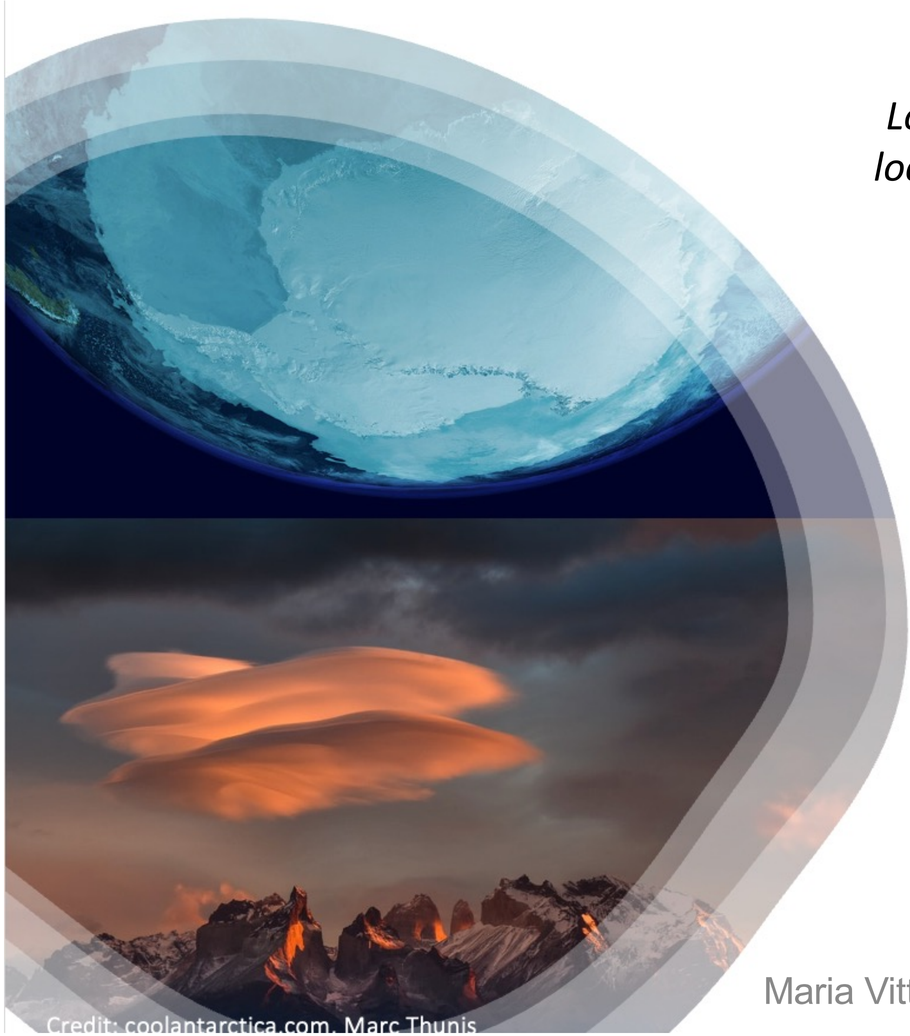
Seminario di Divisione CLIMAR – 13 giugno 2025 ore 10:00



Maria Vittoria Guarino

SSPT-CLIMAR

Sea ice and orographic gravity wave drag (OGWD)



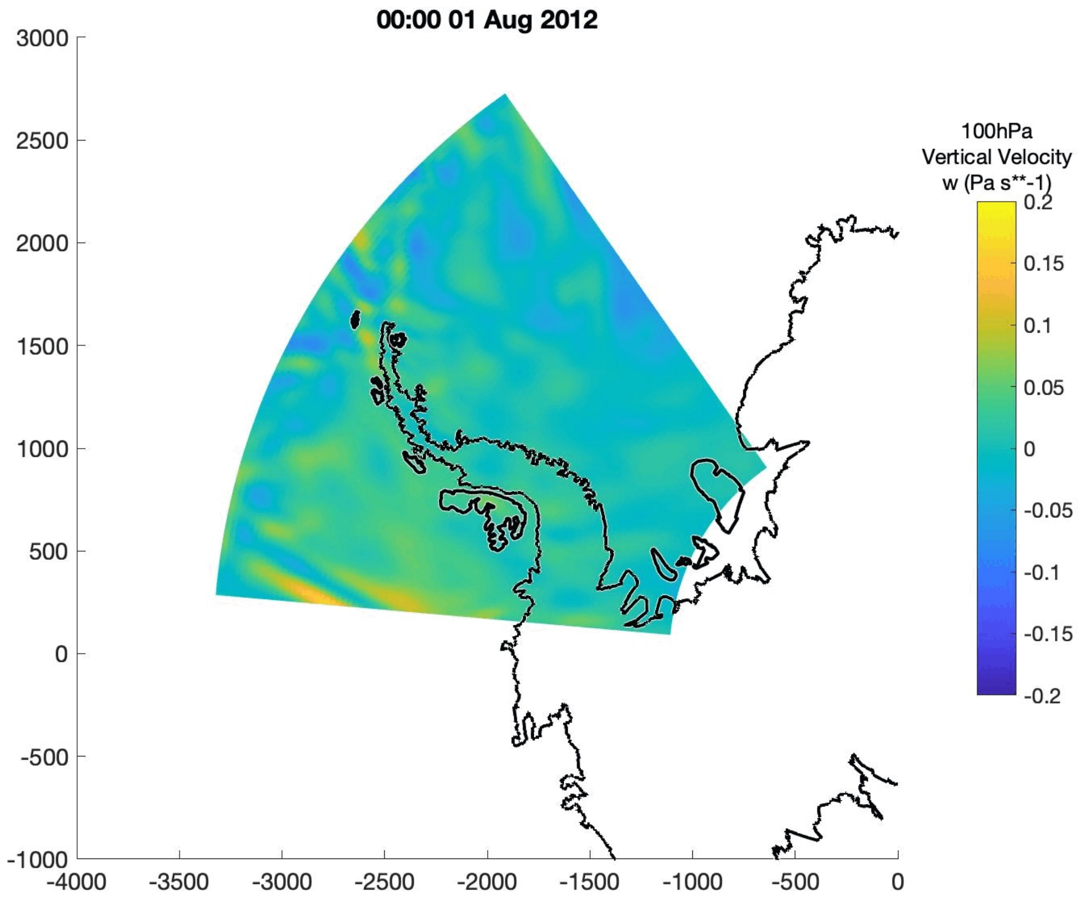
*Low-level winds over Antarctica are **overwhelmingly** controlled by the local orography. They, in turn, exert a large control on sea ice formation and transport.*

Motivations

- Explore the role of OGW drag in the coupled atmosphere-ocean system (traditionally OGWD studies use atm-only configurations)
- Some of the tuning parameters of the UKESM OGWD parameterization are well known to be poorly constrained
- CMIP-type climate models cannot reproduce Antarctic sea ice!

Outline

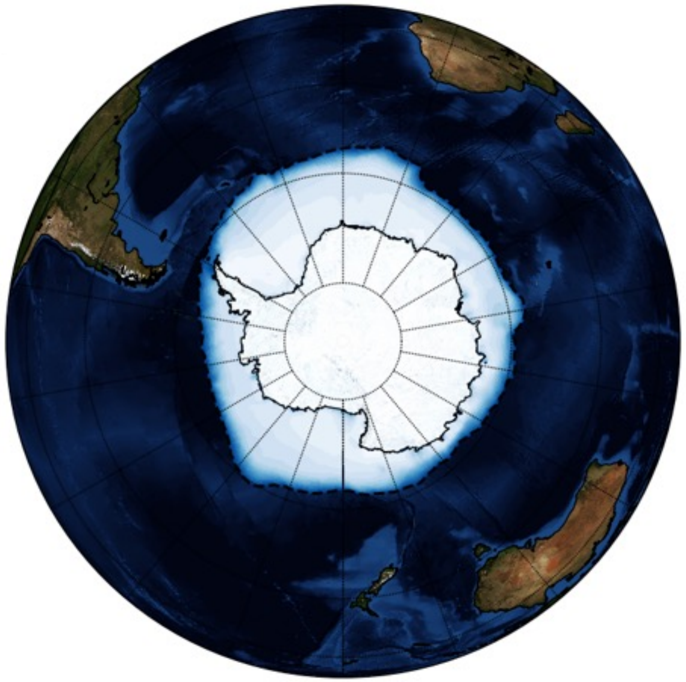
- ***Antarctic Sea Ice***
- ***Antarctic Orography***
- ***OGW Drag and Simulations***
- ***Results (and main conclusions)***
- ***Discussion and Future Work***



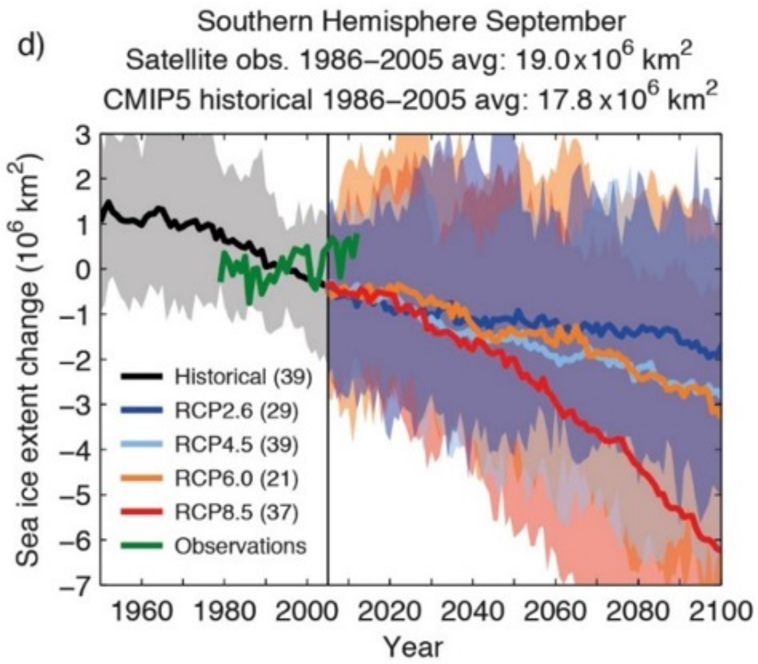
Thanks to Neil Hindley, University of Bath.

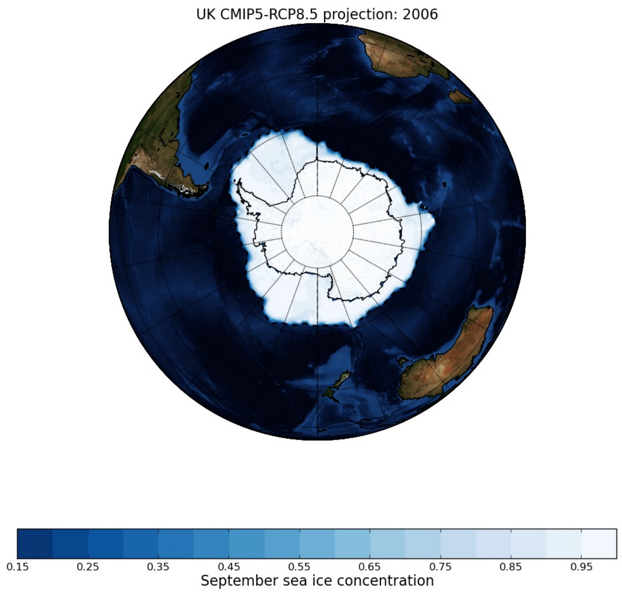
Antarctic Sea Ice

Antarctic Sea Ice

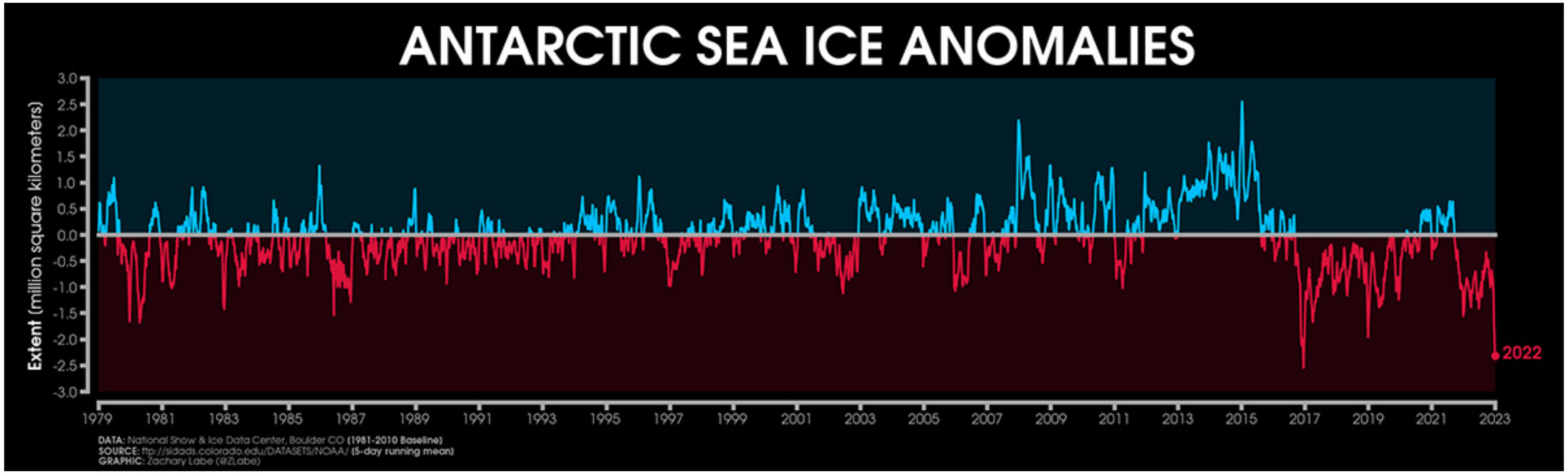


Antarctic Sea Ice





Antarctic Sea Ice



https://www.severe-weather.eu/global-weather/antarctic-sea-ice-extent-record-low-anomaly-observed-rrc/

(IPCC) Fifth Assessment Report (AR5) concluded that:

*"There is "**low confidence**" in climate model projections for Antarctic sea ice due to "the wide inter-model spread and **the inability of almost all of the available models to reproduce** the mean annual cycle, interannual variability, and overall increase of the Antarctic sea ice areal coverage observed during the satellite era"* (Collins et al., 2013).

(IPCC) Sixth Assessment Report (AR6) concluded that:

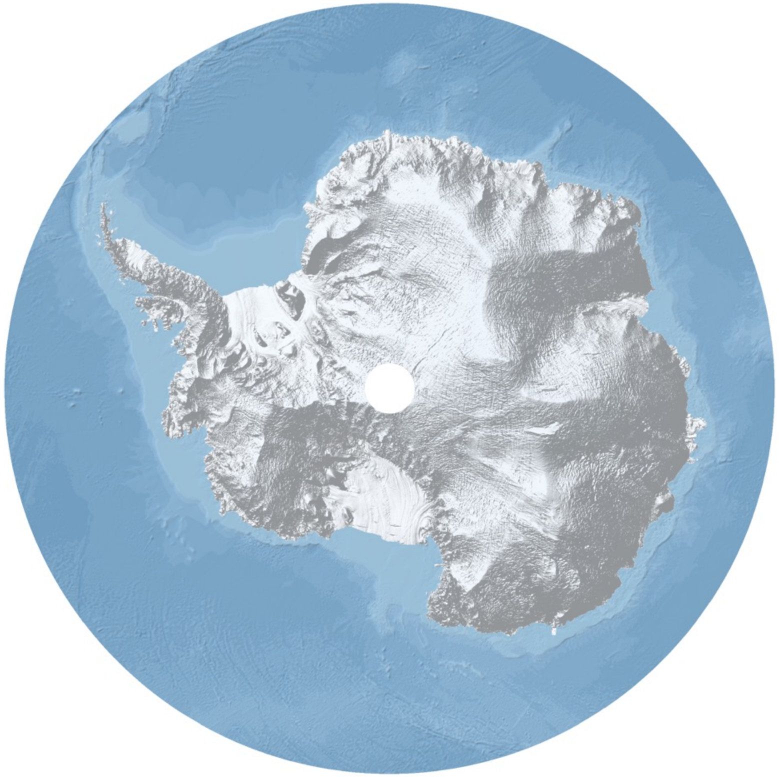
"there is low confidence in model simulations of future Antarctic sea ice decrease, and lack of decrease, due to ***deficiencies of process representation, in particular at the regional level***."

Antarctic Orography

Antarctic
Orography

Mountain wave clouds over Rothera, Antarctica.

Antarctic Orography



"surface winds are overwhelmingly controlled by the orography"

Surface wind speeds are proportional to the slope of the underlying terrain and wind directions are linked to the orientation of the gradient of the terrain (Parish et al., 2006)

https://www.esa.int/Applications/Observing_the_Earth/FutureEO/CryoSat/New_view_of_Antarctica_in_3D

Antarctic Orography

Katabatic Winds

MONTHLY WEATHER REVIEW

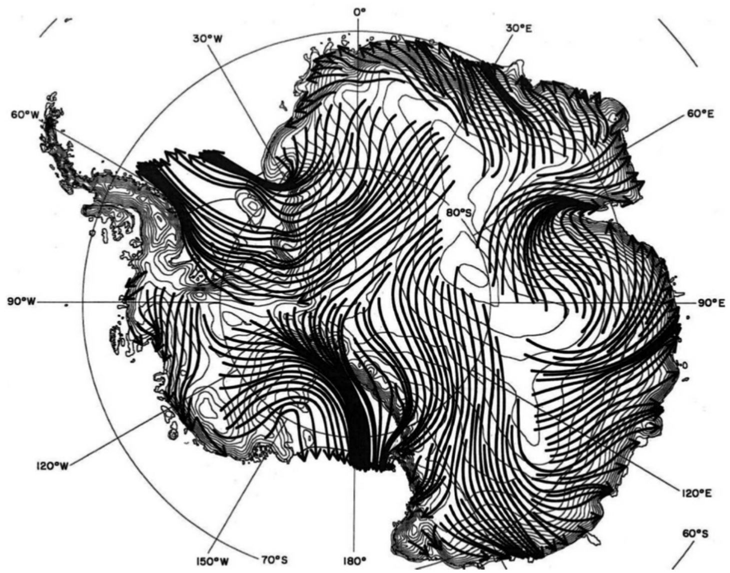
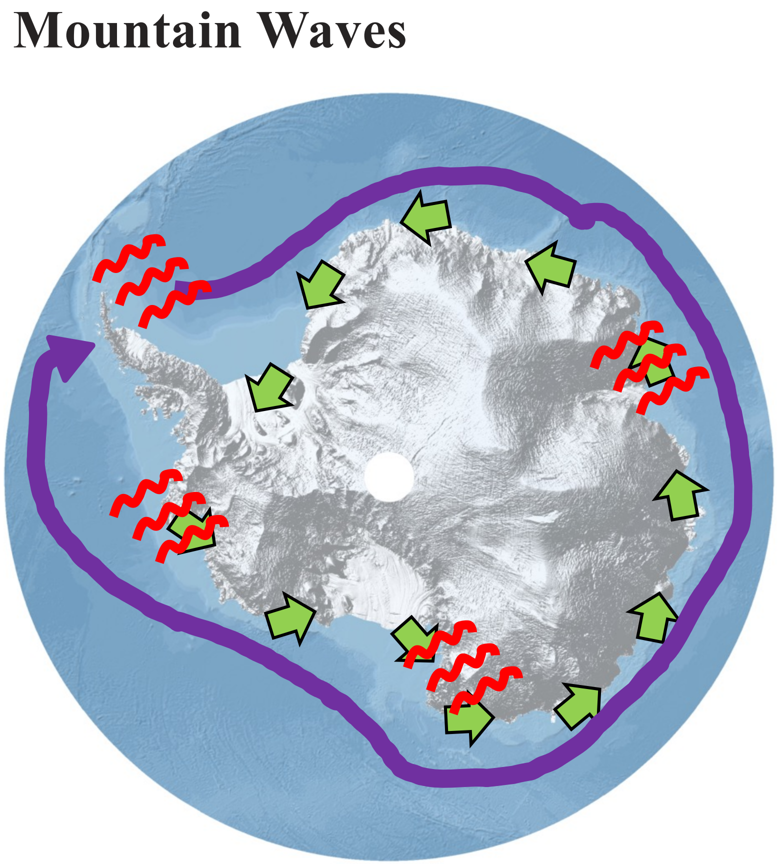


FIG. 3. Mean streamlines at σ = 0.9983 over Antarctica from the June 2003–May 2004 AMPS archive.

"surface winds are overwhelmingly controlled by the orography"

Surface wind speeds are proportional to the slope of the underlying terrain and wind directions are linked to the orientation of the gradient of the terrain (Parish et al., 2006)

Antarctic Orography



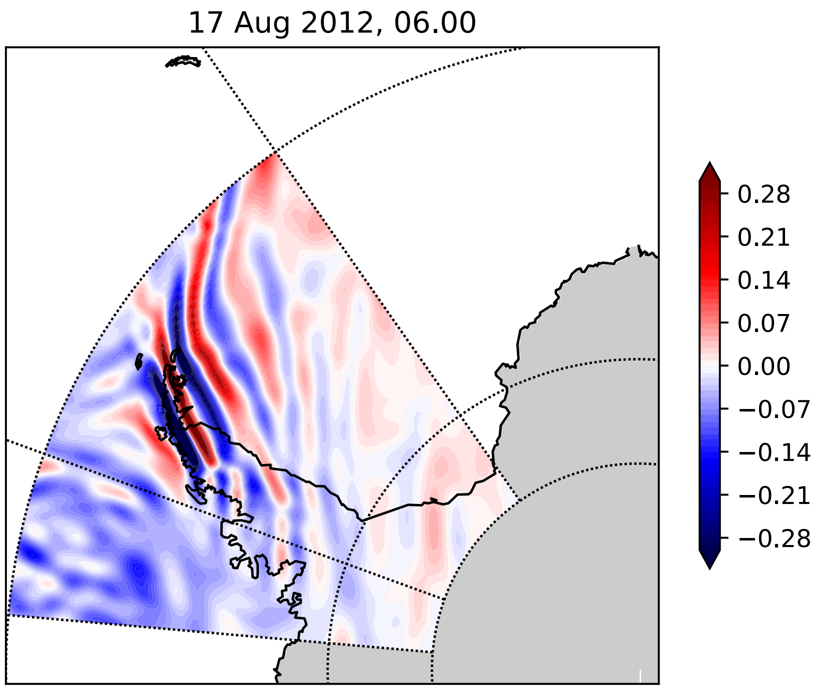
"surface winds are overwhelmingly controlled by the orography"

Easterlies: Mountain waves can be excited by katabatic winds because the uneven steep topography along the coast

Westerlies: the Antarctic Peninsula is a hot spot for Gravity Wave generation (together with the Andes)

Antarctic Orography

Mountain Waves



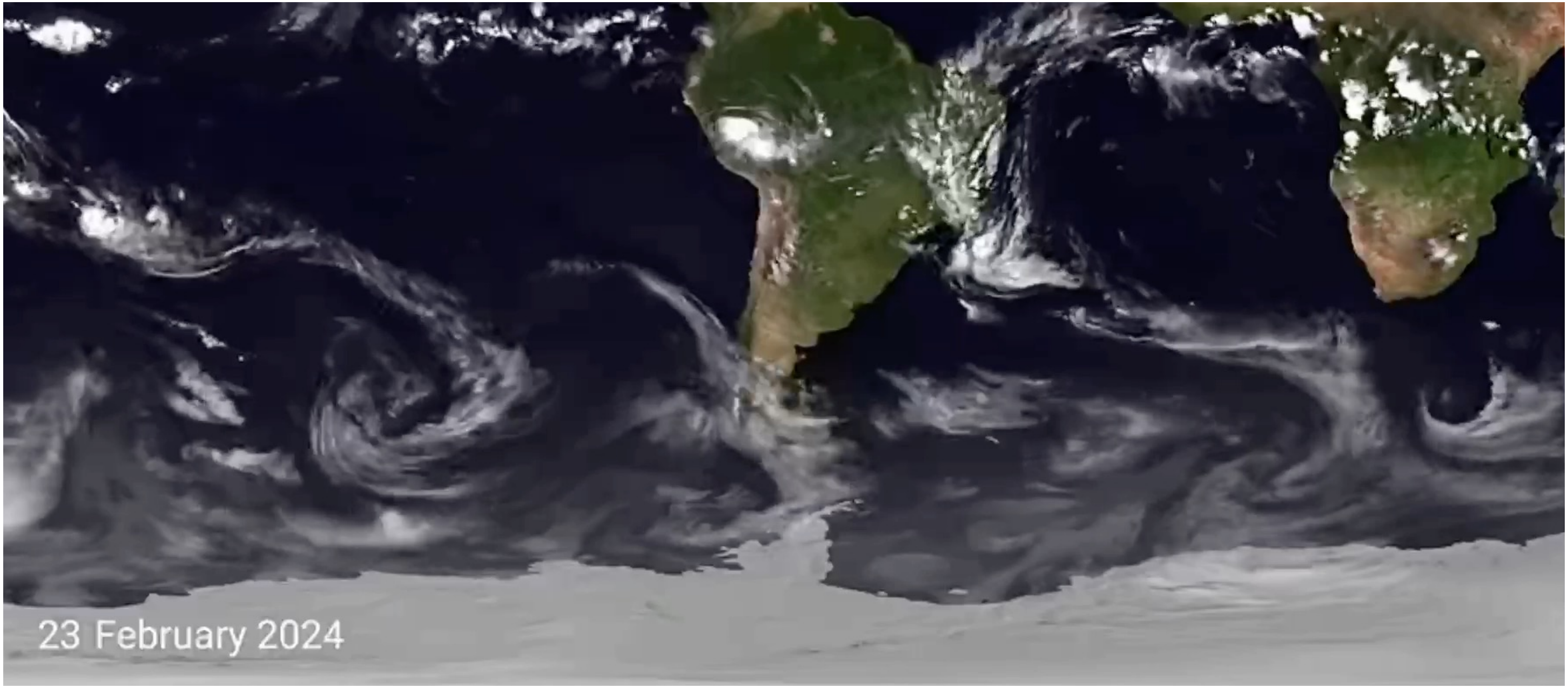
"surface winds are overwhelmingly controlled by the orography"

Easterlies: Mountain waves can be excited by katabatic winds because the uneven steep topography along the coast

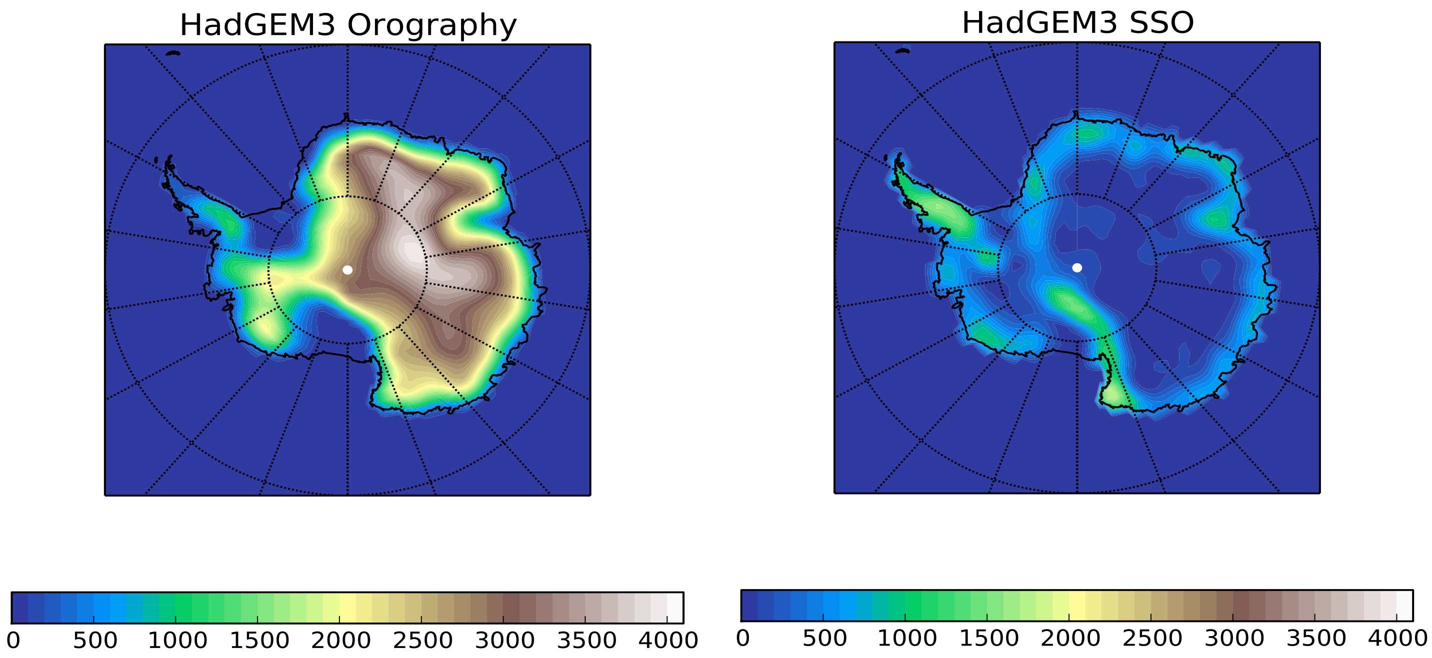
Westerlies: the Antarctic Peninsula is a hot spot for Gravity Wave generation (together with the Andes)

Antarctic Orography

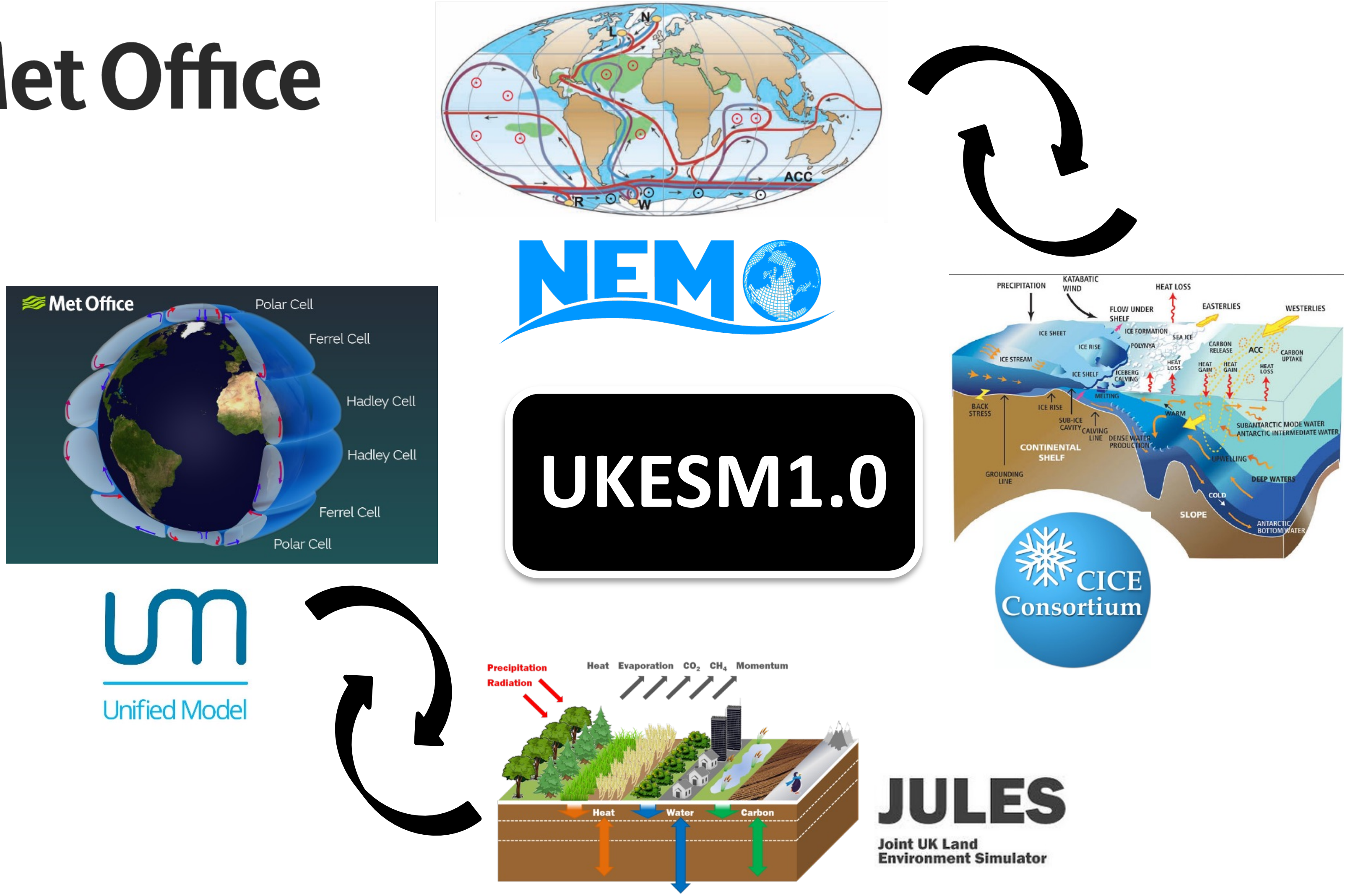
EUMETSAT video: Global weather form Jan to March 2024 (https://www.youtube.com/watch?v=6zU_qg9c7MQ)



Orographic Gravity Wave Drag



Met Office



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Orographic Gravity Wave Drag

In Global Circulation Models, the influence of orography on the climate system is modelled via orographic gravity wave drag (OGWD) parameterizations. Models usually partition the drag exerted on the atmosphere by the ***sub-grid scale*** orography into **two components**: **flow blocking and gravity wave drag**.

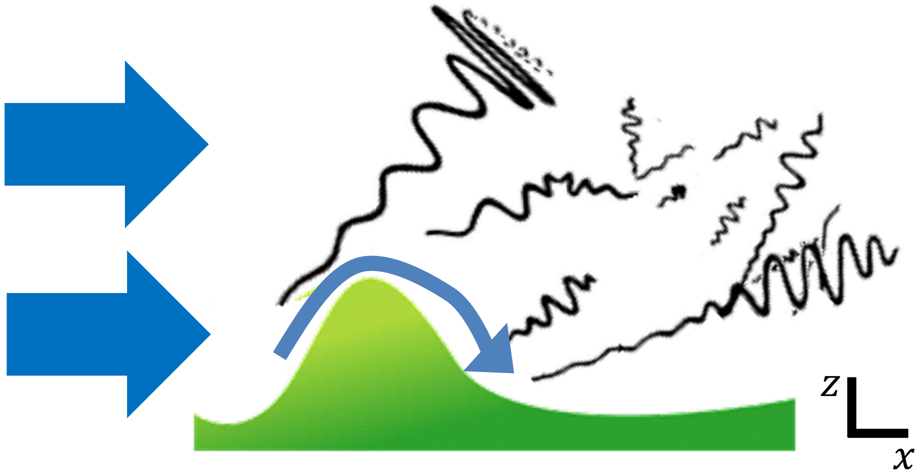
Gravity Wave Regime

- Large scale circulation influenced by gravity wave breaking

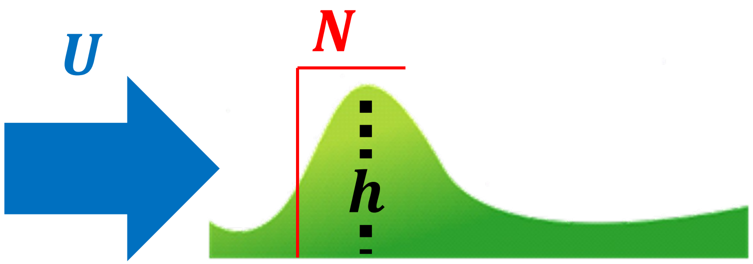
Flow Blocking Regime (3D geometry)

- Surface winds influenced by blocking conditions

Both regimes can influence sea ice via alterations of the atmosphere-ocean coupling



Orographic Gravity Wave Drag



$$\frac{Nh}{U}$$

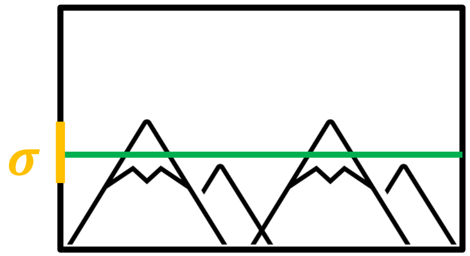
Nh/U >> 1 Flow Blocking Regime
Nh/U << 1 Flow Over Regime (GWs)

In the UM model OGWD parameterization, the local flow regime is computed **in each grid-box** using the sub-grid mountain height h_{sso}, the wind speed U the and static stability N: $\frac{\boldsymbol{Nh_{sso}}}{\boldsymbol{U}}$

$$h_{sso} = n_\sigma * \sigma$$

σ: standard deviation of the sub-grid orography

n_σ: tuning parameter



mean orography
(H on the model grid)

Orographic Gravity Wave Drag

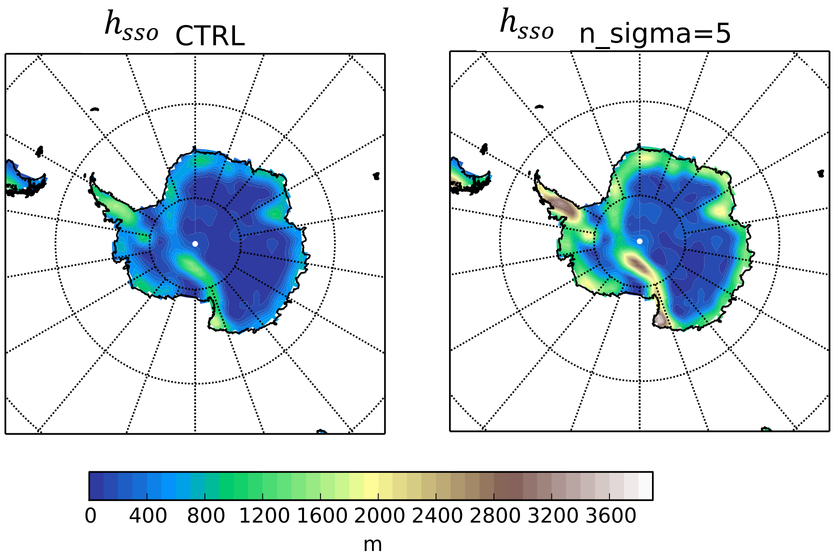
$$h_{sso} = n_\sigma * \sigma$$
$$Nh_{sso}/\mathrm{U}$$

Simulation period: 1950 – 2015 (Historical runs for CMIP6)

HIST:	**CMIP6 Historical run**	$n_\sigma = 2.5\ (default)$
F_OVER:	**Flow Over Regime**	$n_\sigma = 1.5$
F_BLOCK:	**Flow Blocking Regime**	$n_\sigma = 5$

$\boldsymbol{Nh_{sso}/U < 1}$

$\boldsymbol{Nh_{sso}/U \gg 1}$

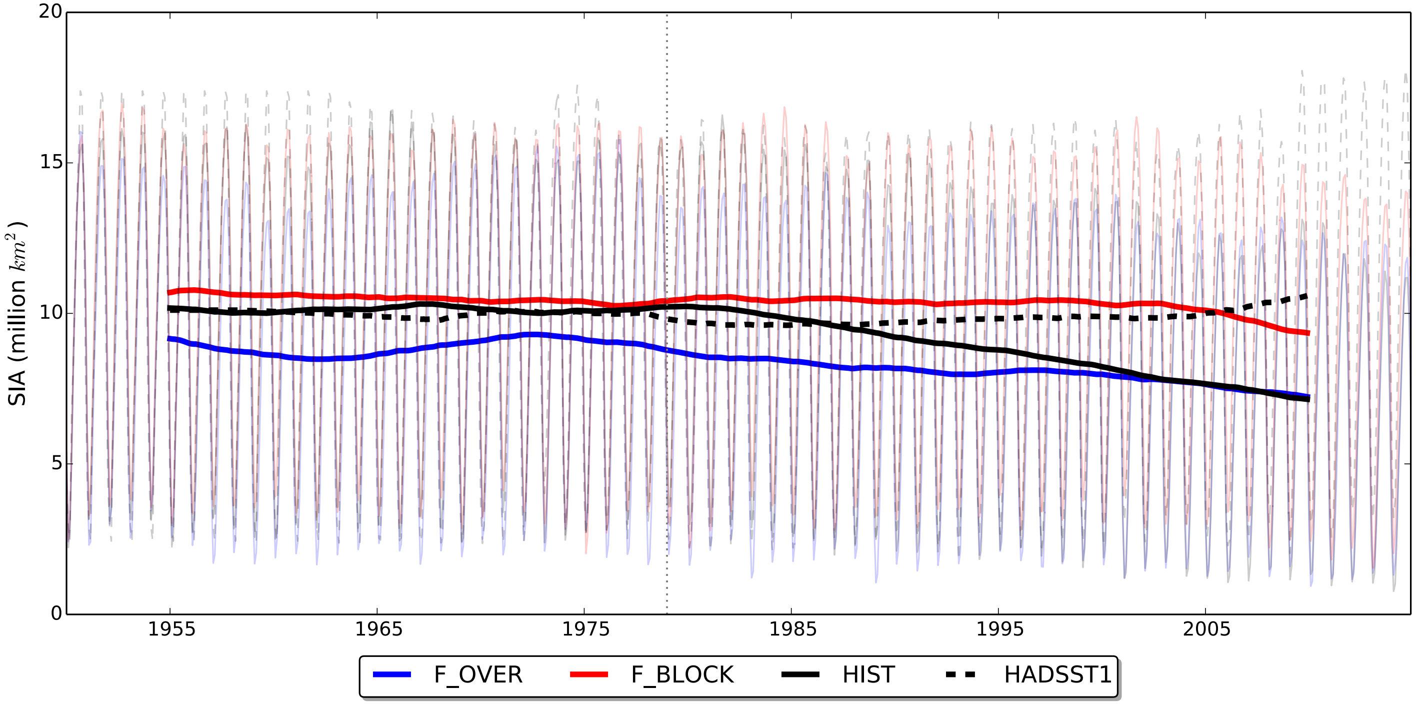


Changes to n_σ were constrained to Antarctica only (*i.e.* below 60°S).

Results

Time-series of sea ice area for all runs and observations (11-year running mean applied):

Figure 1. *Timeseries of sea ice area for observations (dashed line), HIST (black line), F_BLOCK (red line), F_OVER (blue line). Thin lines are monthly means, thick lines are 120-month running means. Dotted vertical line marks the start of the satellite era (1979) after which observations are more reliable-*



Results: Sea Ice

Time-series of sea ice area for all runs and observations (11-year running mean applied):

Figure 1. *Timeseries of sea ice area for observations (dashed line), HIST (black line), F_BLOCK (red line), F_OVER (blue line).*
Thin lines are monthly means, thick lines are 120-month running means.
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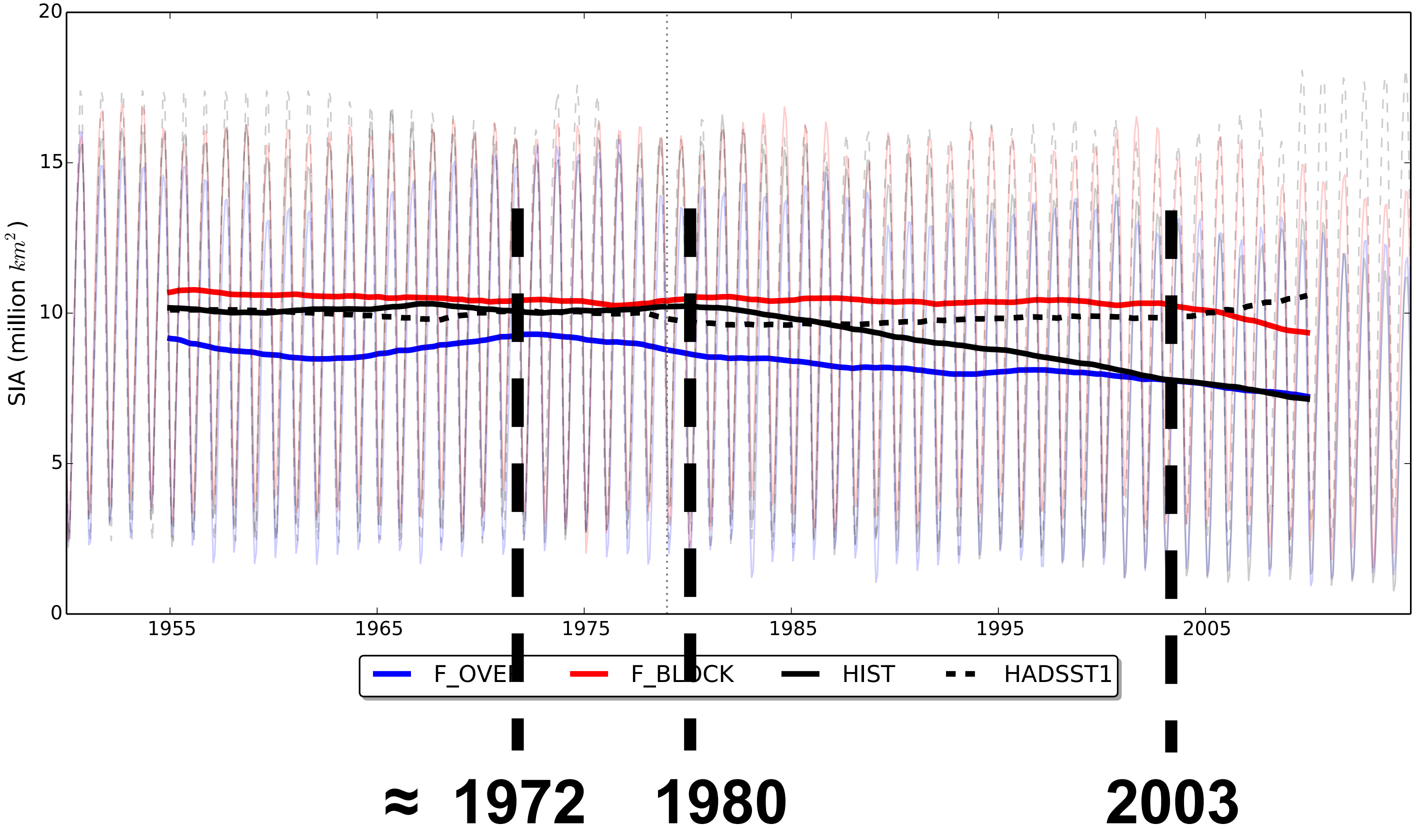
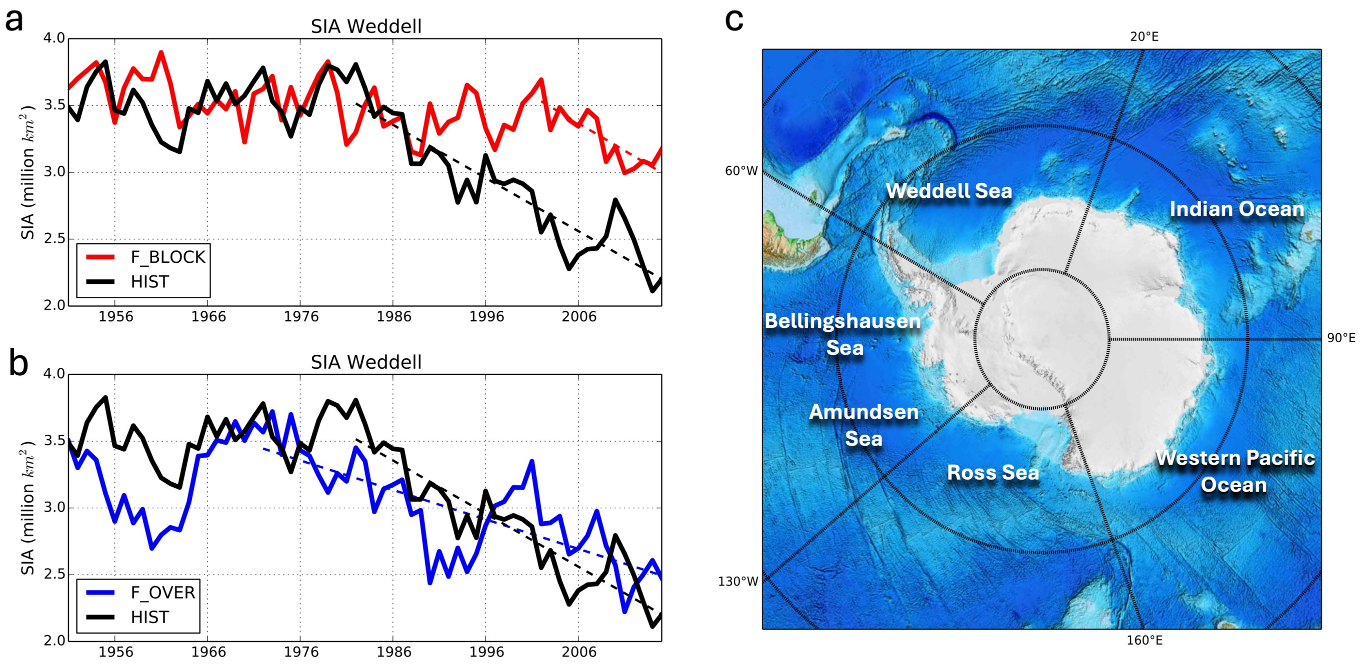


Results: What is making sea ice decline?

The pan-Antarctic signal for sea ice decline is driven by the Weddell Sea sector

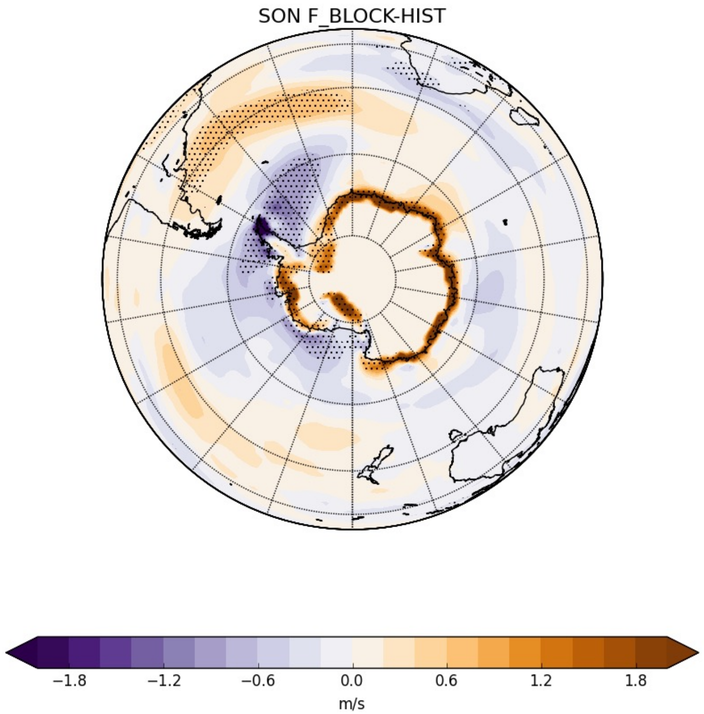
- F_OVER: 1971
- HIST: 1981
- F_BLOCK: 2001



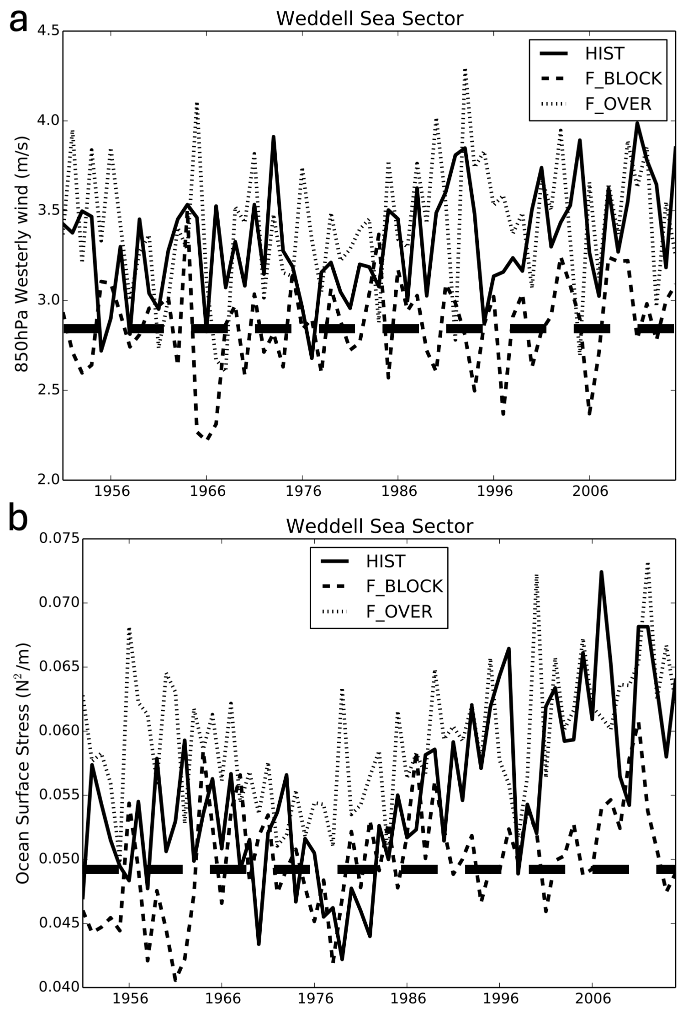
Results: What is making sea ice decline?

Positive MSLP anomaly due to flow blocking conditions over the peninsula:

MSLP and U850hPa anomalies for the Flow Blocking simulation indicates that the Peninsula slows down the incoming flow (flow blocking depth is higher and ‘less’ flow can go past the mountain).



Results: What is making sea ice decline?



Westerlies (U>0) at 850hPa

In F_BLOCK the increased flow blocking from the Peninsula slows down the winds over the Weddell Sea area compared to HIST

$\boldsymbol{\tau_o}$

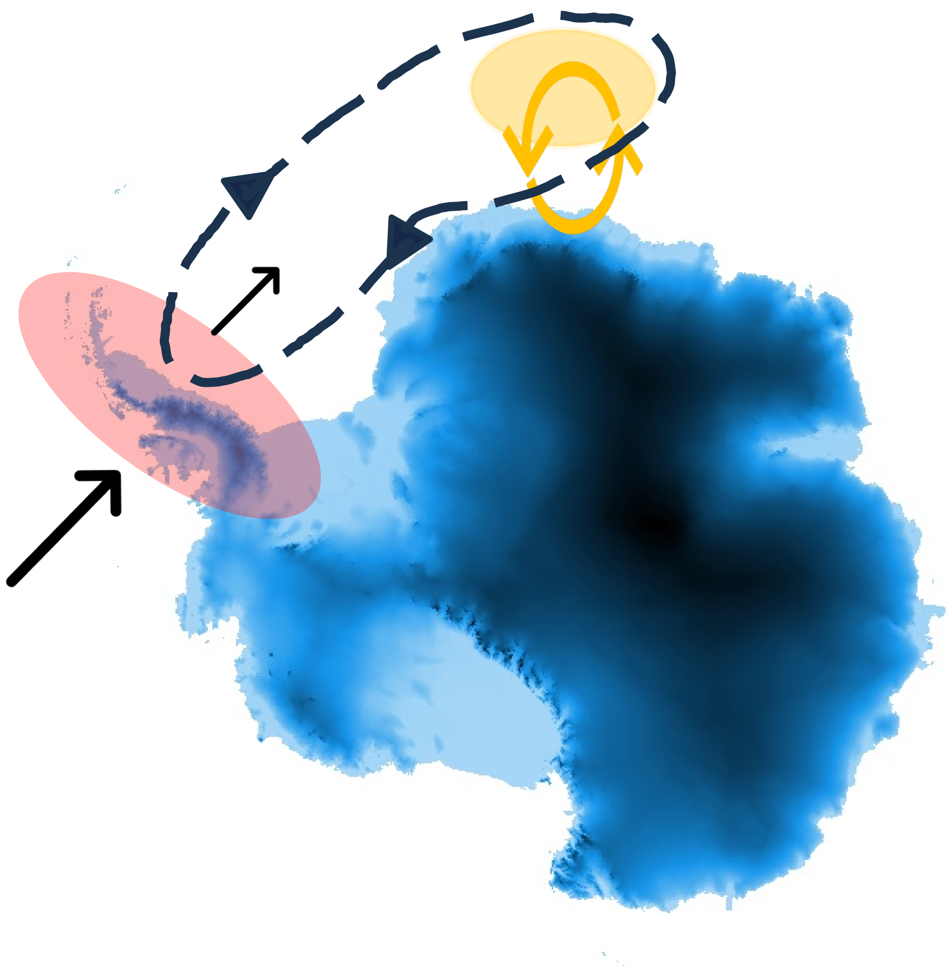
(total ocean surface stress: atm+ice)

$$\tau_o = \alpha\tau_{io} + (1-\alpha)\tau_{ao}$$

$$\tau_{io} = \rho_o C_{io}|(u_i - u_o)|(u_i - u_o)$$

$$\tau_{ao} = \rho_a C_{ao}|u_a|u_a$$

Results: What is making sea ice decline?



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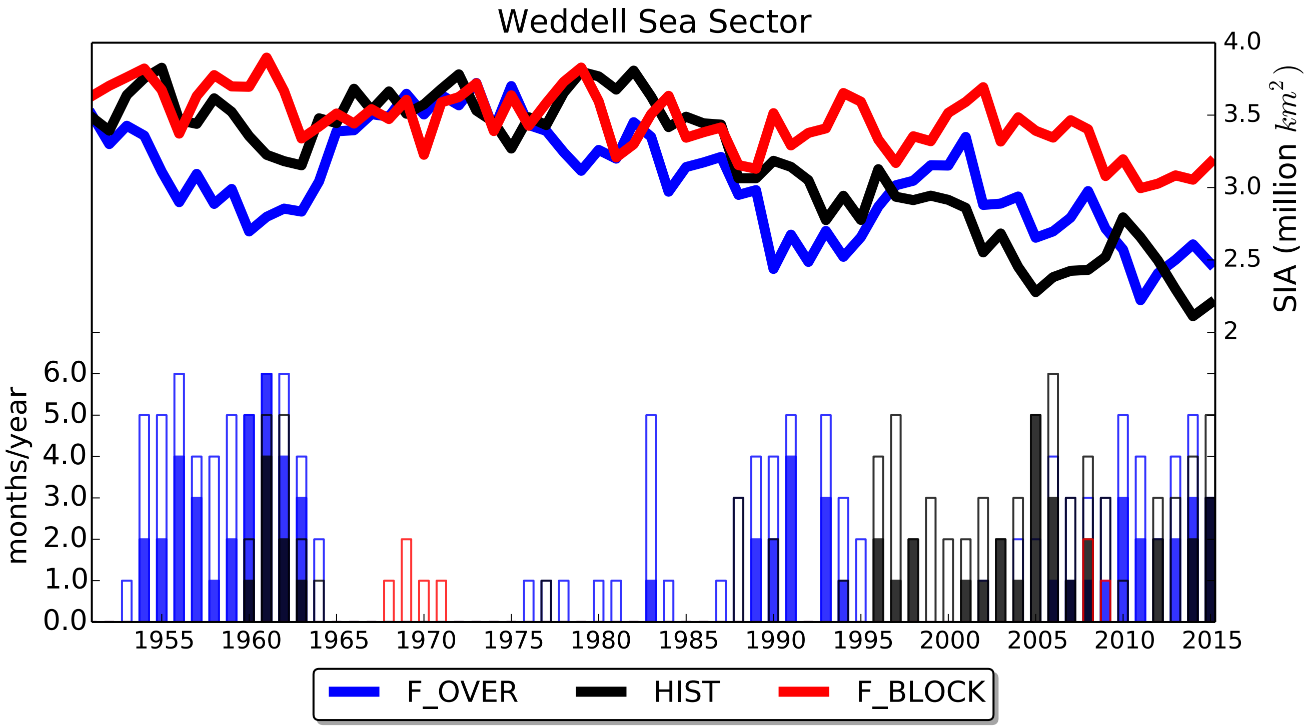
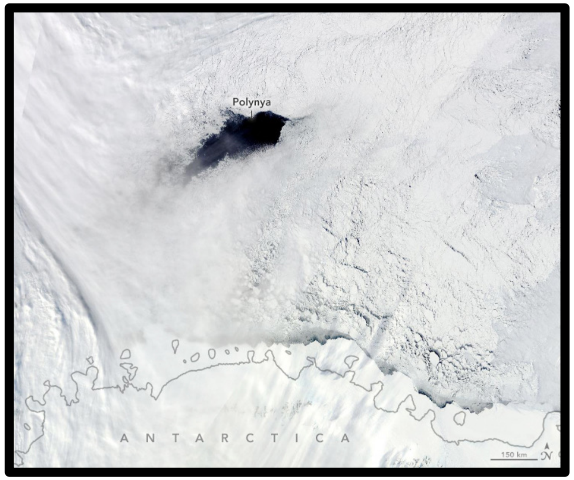
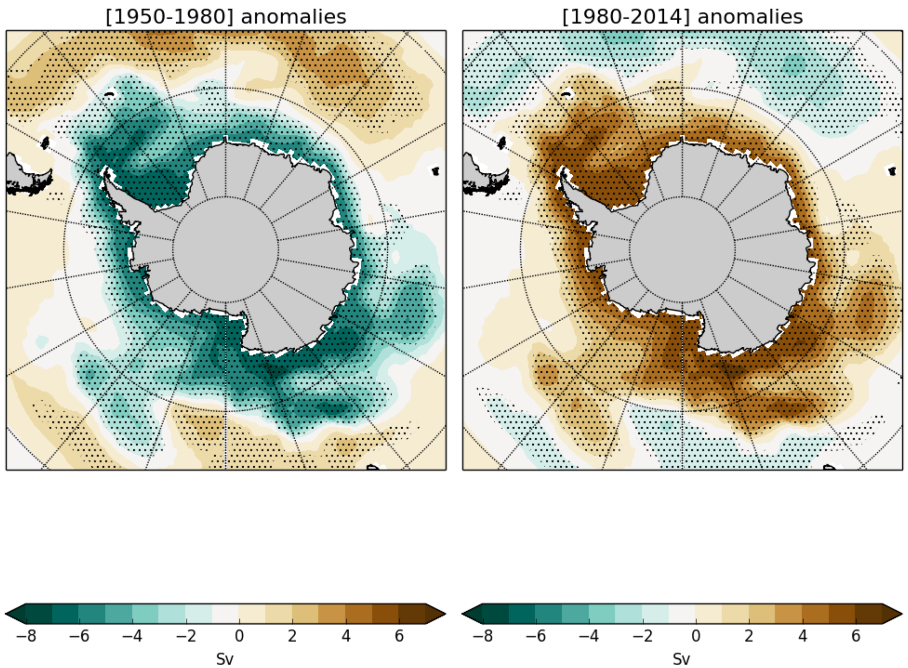


GW drag -> Winds ->
surface ocean stress -> Deep convection



bars: number of months per year in which Mixed Layer Depth > 2000 m
filled bars: number of months per year in which Mixed Layer Depth > 2000 m and convection area is at least 80,000 km^2

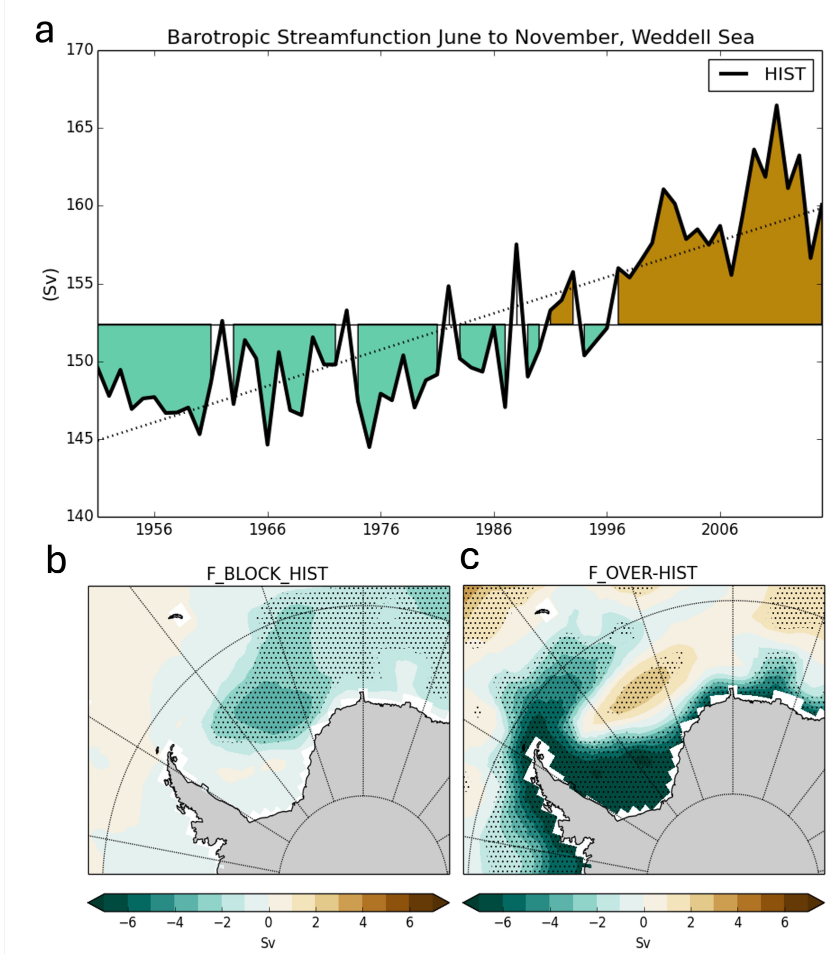
Results: What is making sea ice decline?



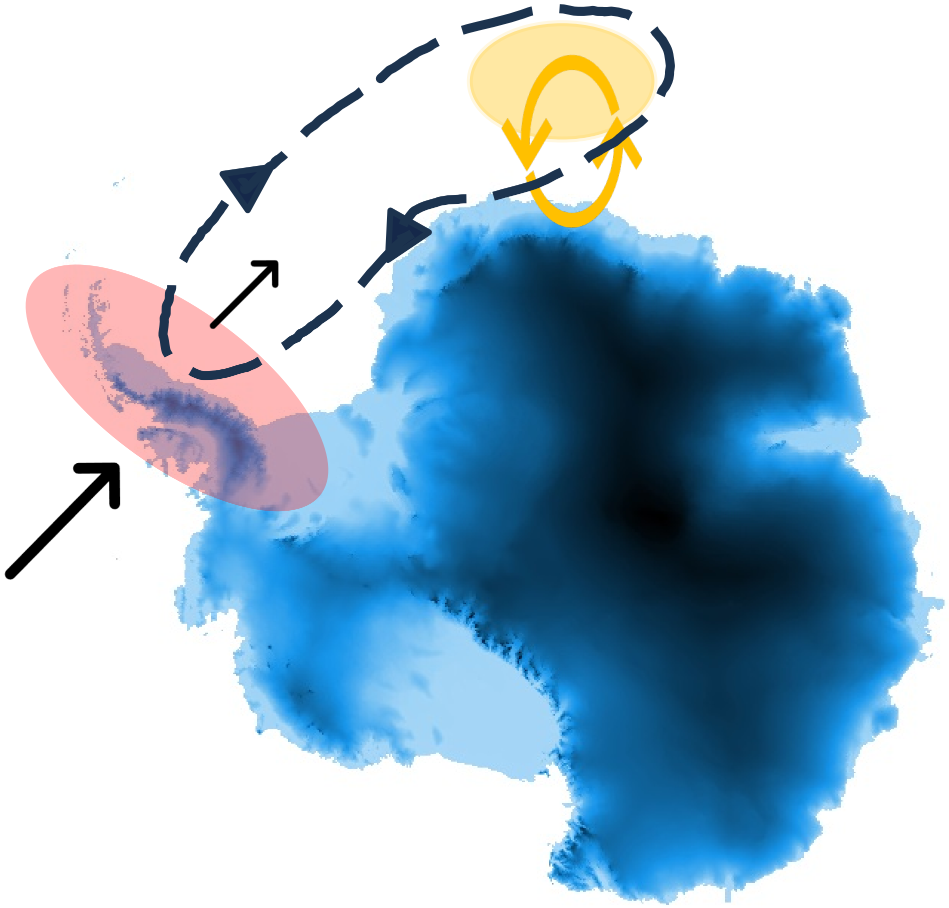
Annual anomalies for first (left) and second (right) part of Historical period as simulated by HIST:

Left panel: $\text{BaroSF}_{[1950\text{-}1980]}\text{-}\text{BaroSF}_{[1950\text{-}2015]}$

Right panel: $\text{BaroSF}_{[1980\text{-}2014]}\text{-}\text{BaroSF}_{[1950\text{-}2015]}$

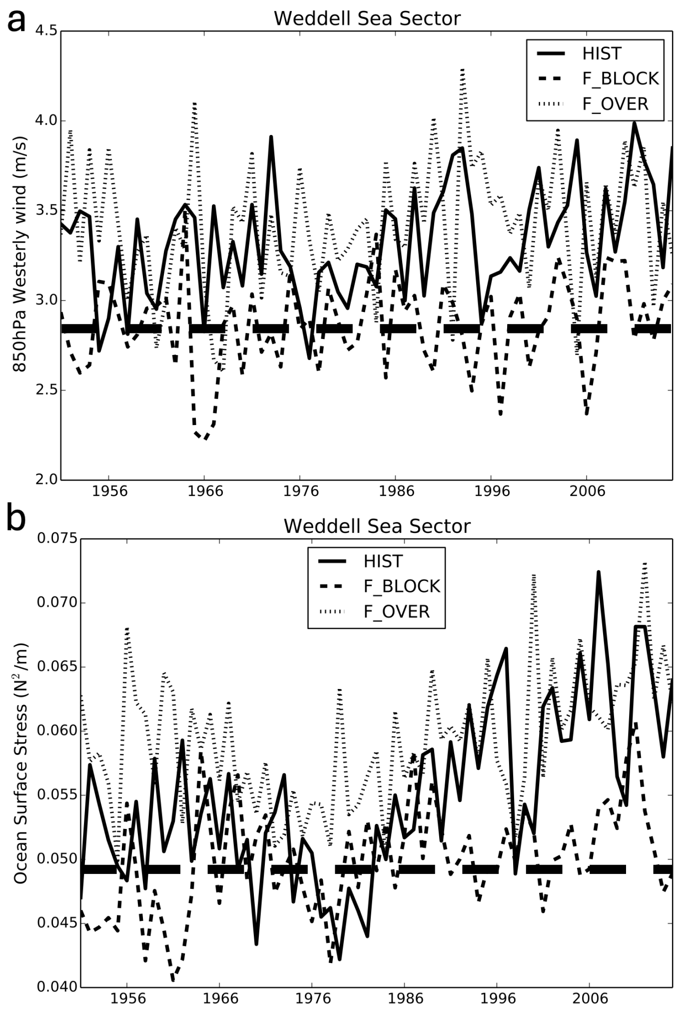


Conclusion 1



Conclusion n1:
The pathway through which OGWD influences sea ice is via modifications of the flow regime across the peninsula and thus the surface winds across the Weddell sea sector, which in turn alters the occurrence of oceanic deep convection.
This happens because the peninsula, hot spot of gravity waves, exerts a large control on the surface wind fields on both the windward side (Bellingshausen and Amundsen seas sector) and the lee side (Weddell sea sector) of the mountain ridge.

Results: A transition for the Historical



Transition for HIST

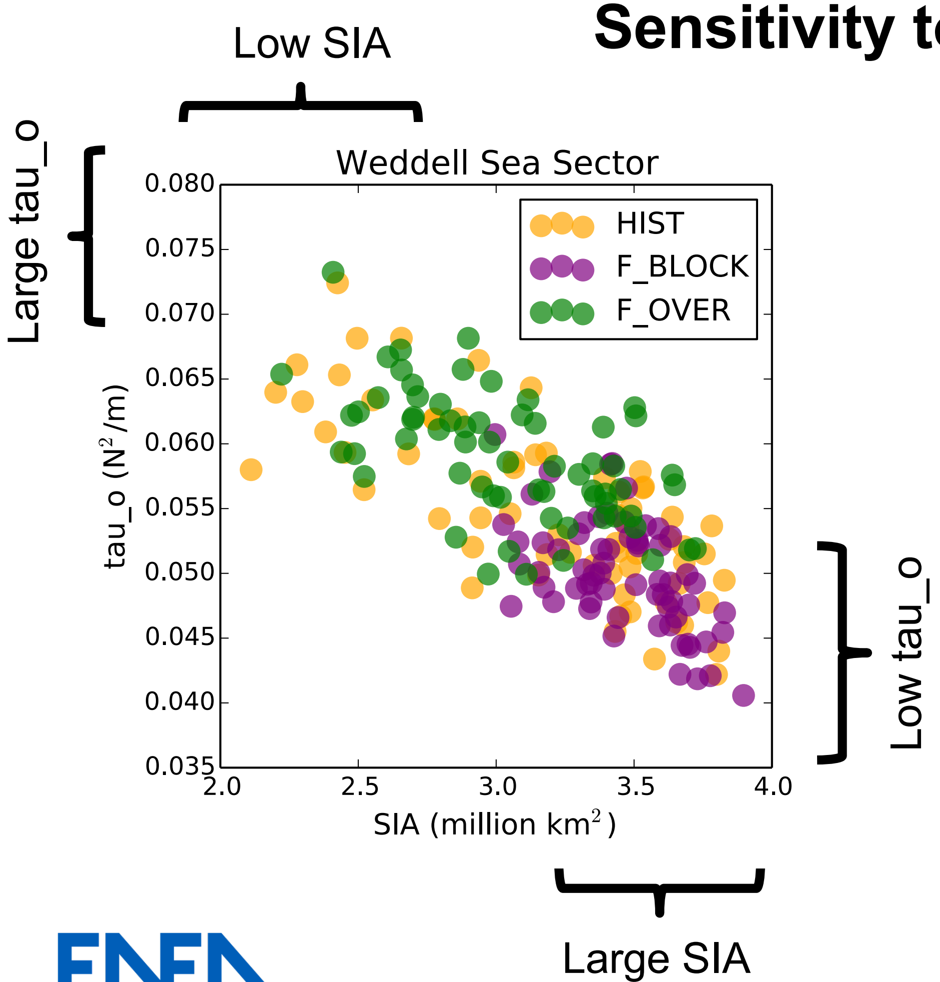
HIST: positive trend in the westerlies since 1980
(about same time sea ice begins decline).

F_BLOCK: no trend.

- HIST and F_BLOCK differ the most as time goes by.
- For the first 30 years of simulation, the 850hpa winds for the runs are (more) similar as there is significant variability in both runs.
- In the last 35 years HIST and F_BLOCK grow apart and seem representing two different states. This transition is particularly visible in the ocean surface stress. Interestingly, HIST becomes more similar to F_OVER towards the end of the run, which represents a flow over regime situation.

Results: A transition for the Historical

Sensitivity to strong winds



GW drag -> Winds ->
surface ocean stress -> Deep convection

In a strong wind state the model is more prone to initiate open ocean deep convection that melts the sea ice.

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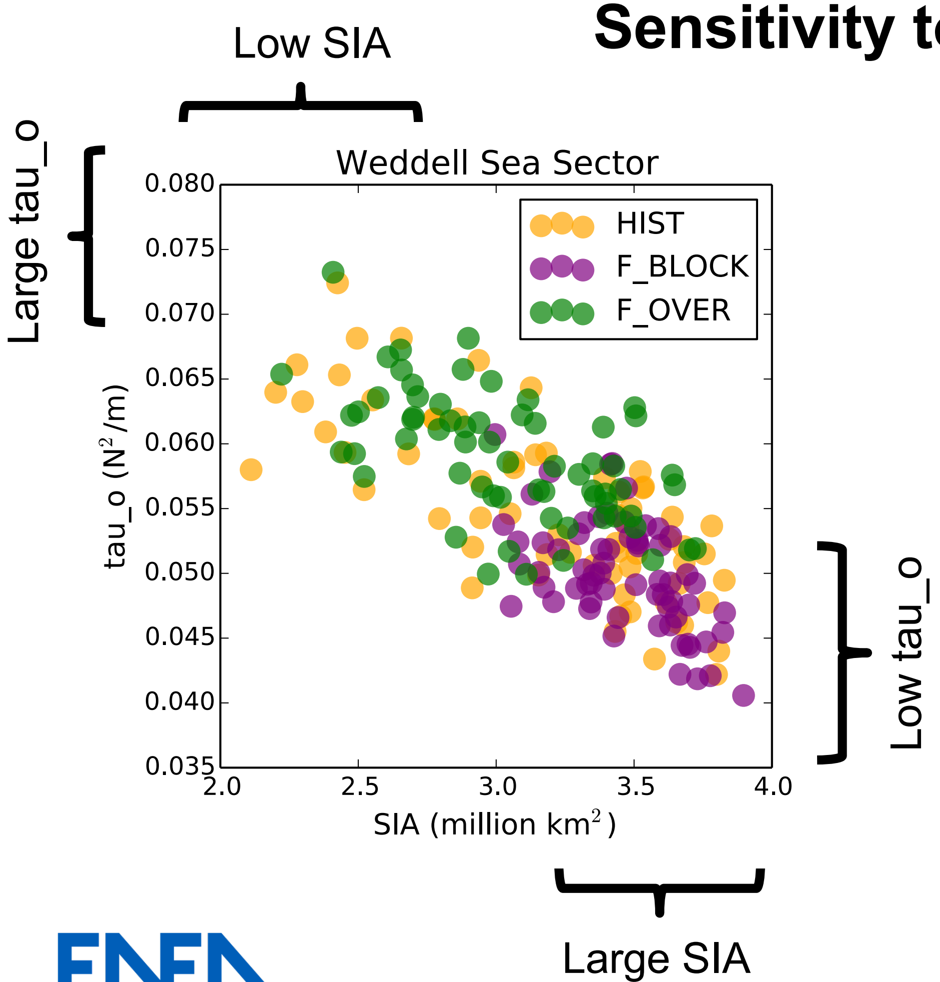
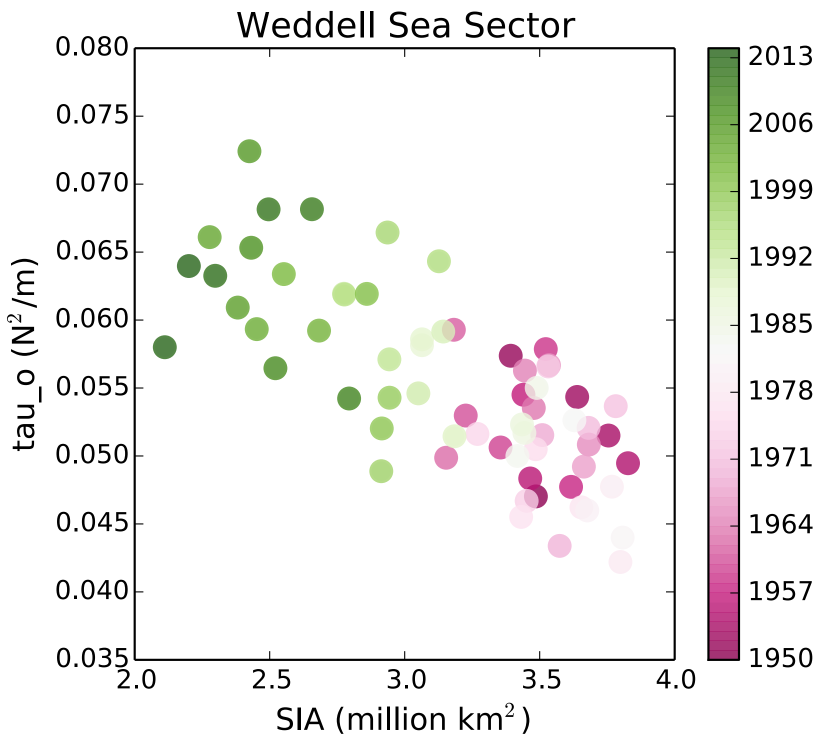
Results: A transition for the Historical

Sensitivity to strong winds





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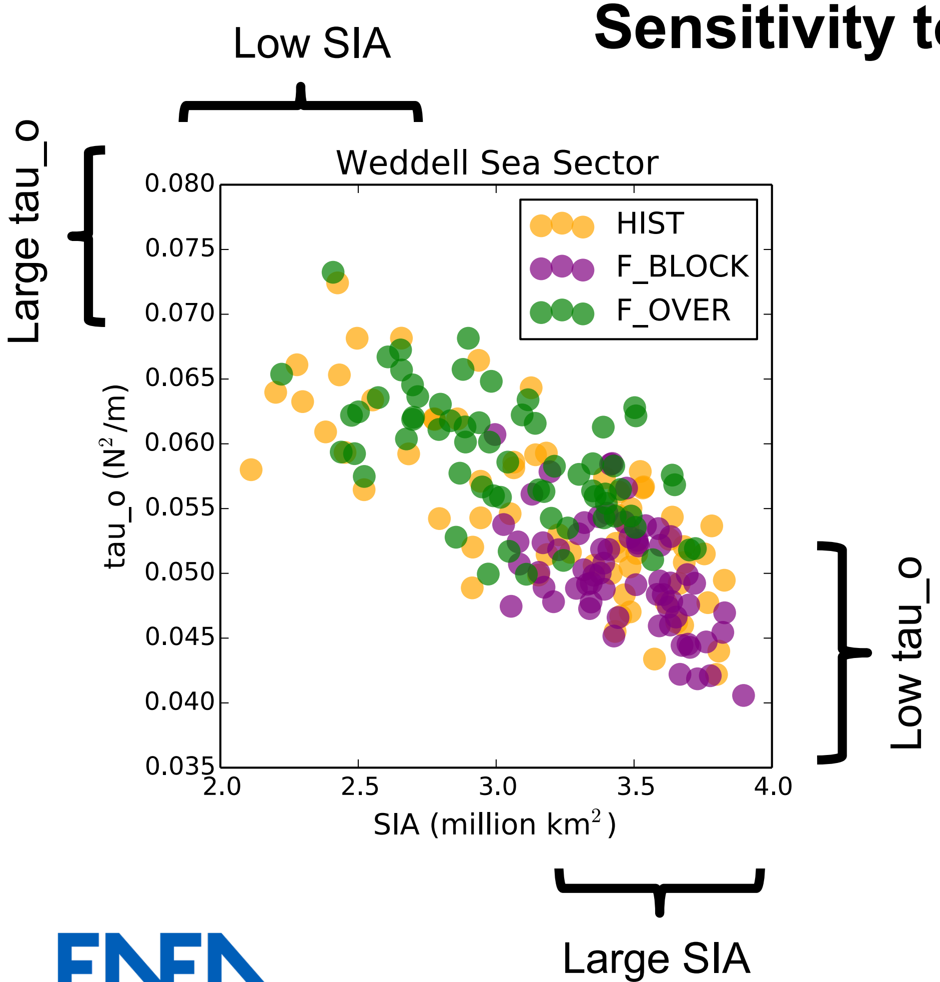
Conclusion 2

Sensitivity to strong winds



***Conclusion n2:** in the HadGEM3 model there exist an anticorrelation between the total ocean surface stress and the sea ice area.*
In a strong wind state the model is more prone to initiate open ocean deep convection that melts sea ice.

During the historical period, HadGEM3 transitions from a low tau_o/large SIA to a high tau_o/small SIA state. These two regimes are well captured by the Flow Blocking and Flow Over sensitivity experiments, where changes to the surface winds are imparted by the different orographic gravity wave drag.

Can we use the sensitivity experiments to identify thresholds for mean tau_o, wind speed and wind stress curl that are likely to lead to deep ocean convection?

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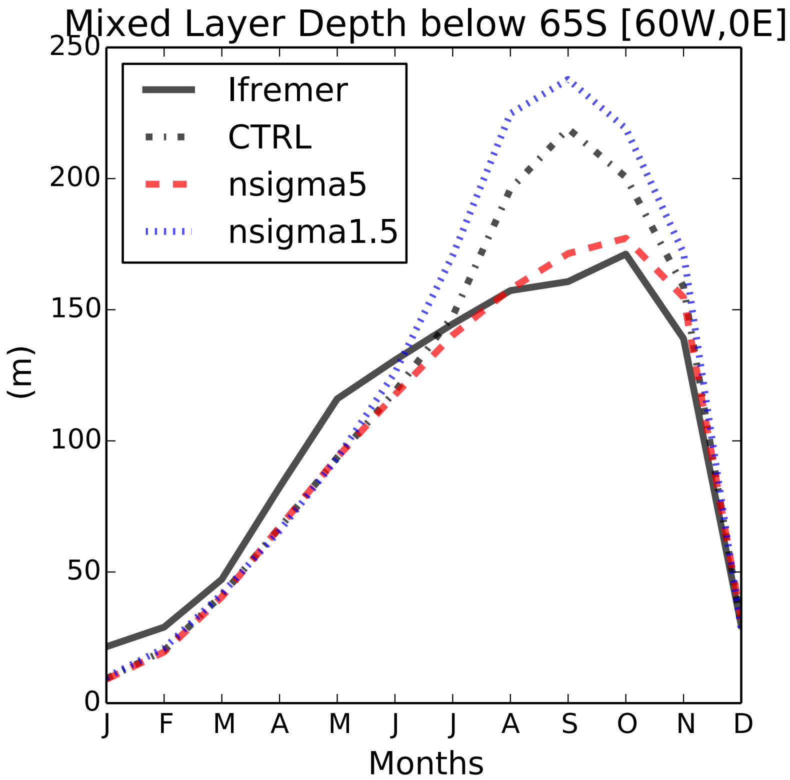
Discussion

Sea Ice Modelling



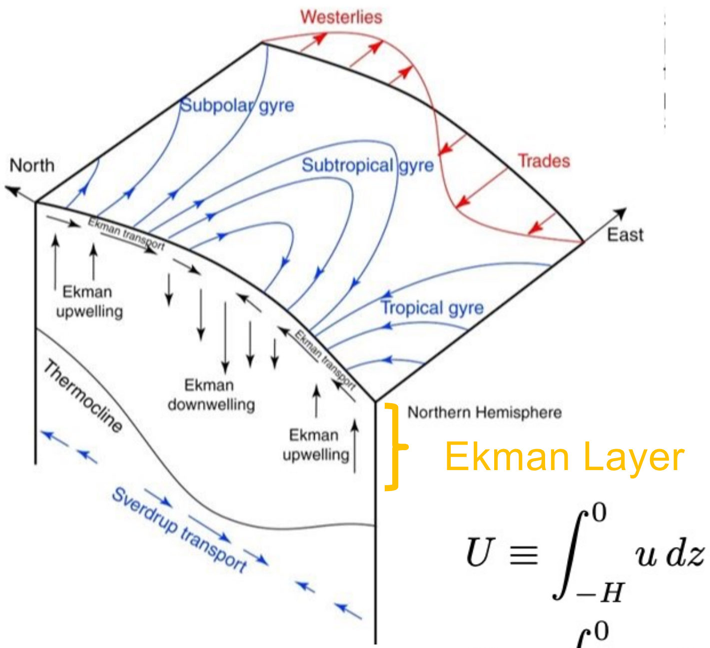
Is the HadGEM3 model too sensitive to changes in the surface wind stress?

Note that the trend in surface winds simulated by the model is real, the subsequent sea ice decline is not!

- **The role of vertical mixing parameterizations vs large scale processes**
- **MLD , 'spurious' Open Ocean deep convection and Antarctic Bottom water formation in coupled climate models**

Sea Ice Modelling

Is the HadGEM3 model too sensitive to changes in the surface wind stress?



$$U \equiv \int_{-H}^{0} u\,dz \quad = \quad \frac{\tau_w^y}{\rho f}$$

$$V \equiv \int_{-H}^{0} v\,dz \quad = \quad \frac{-\tau_w^x}{\rho f}$$

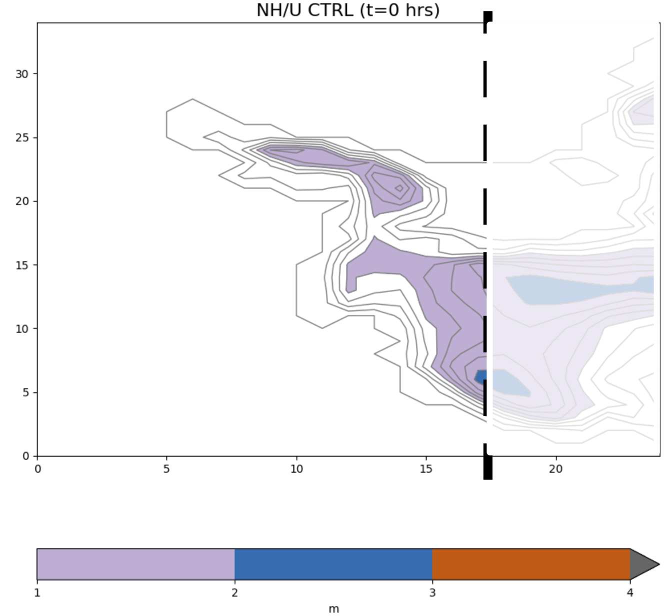
source: Talley et al 2012

Ekman transport depends only on wind tress and Coriolis!
(not on eddy diffusivities)

OGWD and sea ice

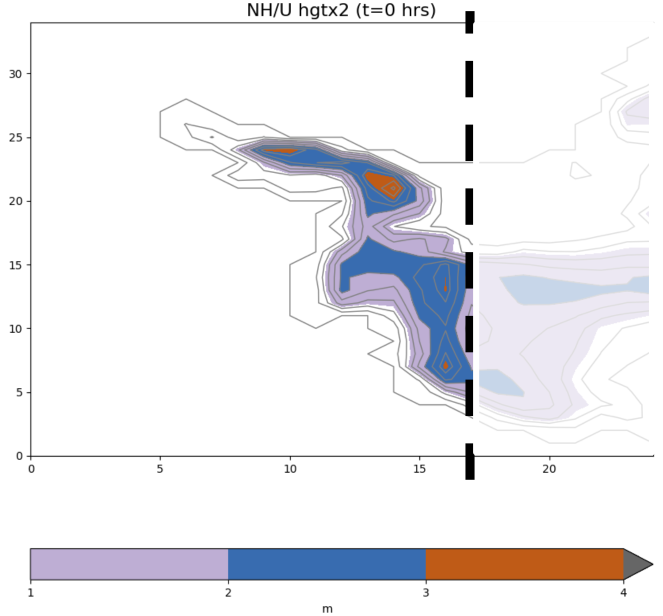
Non-dimensional mountain height: $\dfrac{Nh}{U} = x$

IDEAL_CTRL



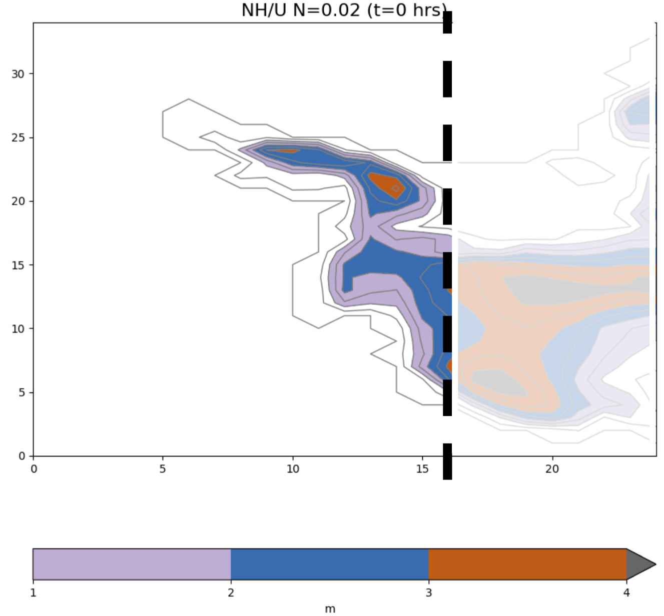
U=10 m/s,
real orography (HGT)
N=0.01 s-1

ERA5_hgtx2



U=10m/s
HGTx2 over peninsula
N=0.01 s-1

ERA5_N002



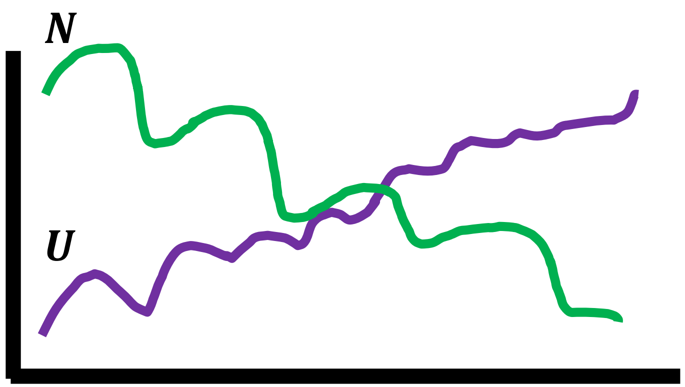
U=10 m/s,
real orography (HGT)
N=0.02 s-1

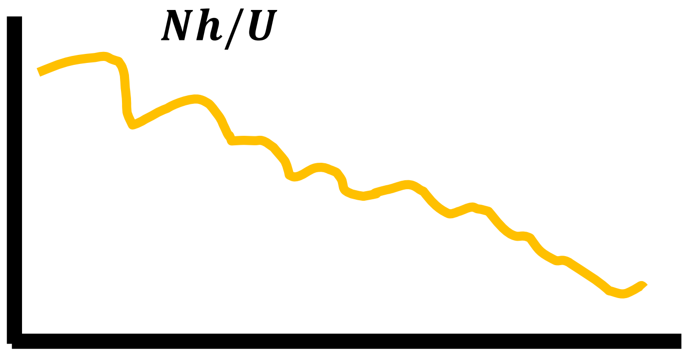
OGWD and sea ice

While in F_BLOCK and F_OVER we pushed the system towards different flow regimes by changing the sub-grid mountain height, in reality $\frac{Nh}{U}$ can change via changes in N and U.

$\frac{Nh}{U}$ is susceptible to short- and long-term trends in surface winds and atmosphere stability, all quantities sensitive to climate change.

1. A change in the prevalent flow regime over the Antarctic Peninsula will have impacts on sea ice too.



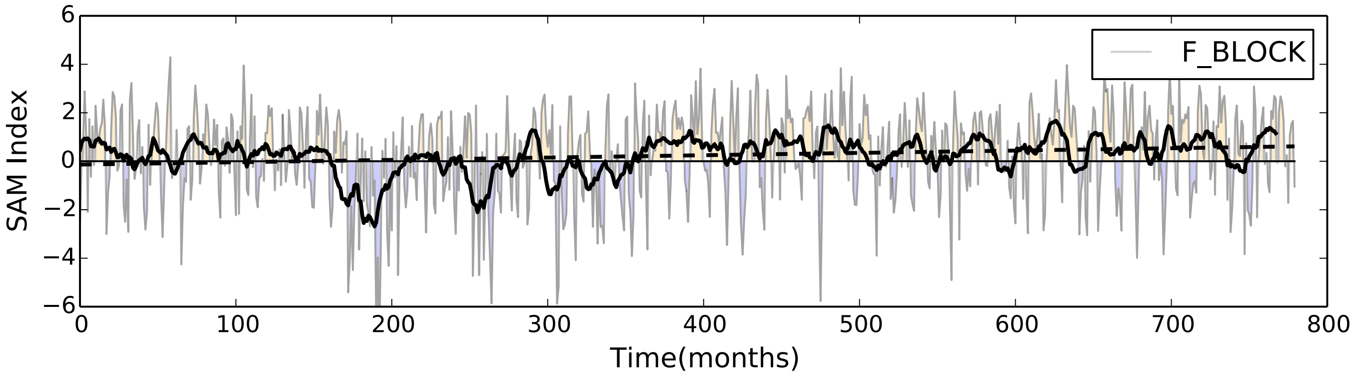


OGWD and sea ice

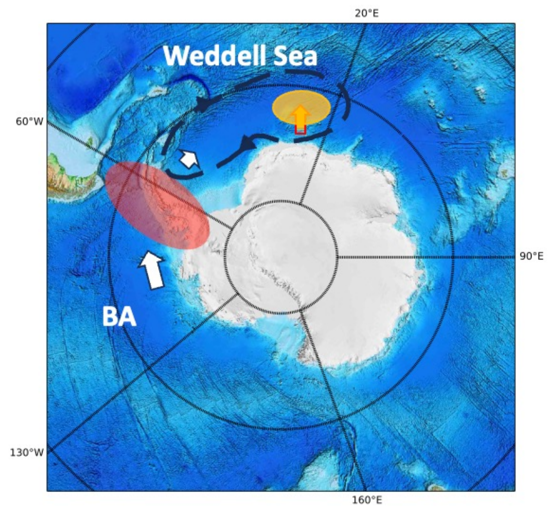
While in F_BLOCK and F_OVER we pushed the system towards different flow regimes by changing the sub-grid mountain height, in reality $\frac{Nh}{U}$ can change via changes in N and U.

$\boldsymbol{\frac{Nh}{U}}$ **is susceptible to short- and long-term trends in surface winds and atmosphere stability, all quantities sensitive to climate change.**

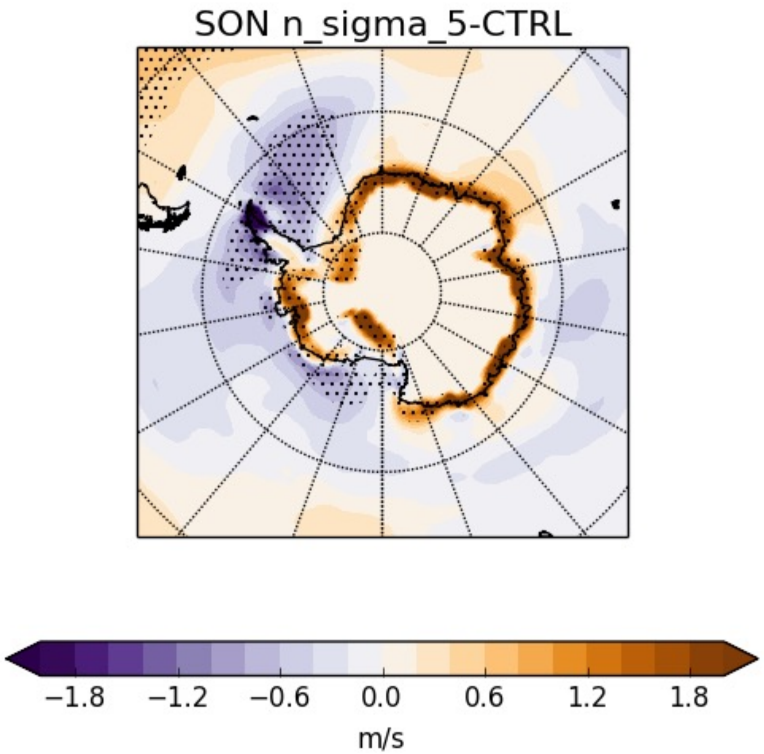
2. The type of flow regime across the peninsula can be more important than large scale configurations in deciding the system response.



Flow Blocking from Peninsula:



Conclusion 3



SON U850 hPa wind anomalies for F_BLOCK-CTRL. Dots indicate statistical significance.
The Peninsula slows down the incoming flow upstream and downstream. In F_BLOCK, westerlies are weak in the Weddell Sea despite the prevalently positive SAM.

Conclusion n3 : Changes in the type of flow regime across the peninsula, and not simply changes in the large-scale winds, should be considered to more accurately predict atmosphere-ocean-ice coupling in the Weddell Sea Sector (a more positive/negative SAM not necessarily means stronger/weaker winds over the Weddell).

Grazie per l'attenzione