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CLIMATE-ICE-OCEAN DYNAMICS OF ANTARCTICA'S COAST AND ICE SHELVES

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262

Assessing controls on Antarctic Peninsula glacier dynamics using a numerical ice flow model

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Since the collapse of the Larsen A and B ice shelves on the eastern Antarctic Peninsula, ice flow from the shelves' former tributary glaciers has accelerated significantly. Here, I use a numerical ice flow model to investigate the influence of changing ocean conditions on Crane Glacier, former Larsen B tributary, following the collapse of the ice shelf. Specifically, I use high-resolution satellite imagery observations of speed, terminus position, and elevation change, bed elevations from NASA's Operation Ice Bridge mission, surface mass balance estimates from the RACMO2.3 climate model, and tune the calving and submarine melting parameterizations that define the ocean boundary conditions to calibrate the numerical model so that it reproduces temporal patterns in speed and elevation. The calving and submarine melting parameterizations are tuned using observations of terminus position (for calving) and surface meltwater runoff and iceberg melting (for submarine melting) to assess the influence of ocean change on changes in glacier dynamics. This research will contribute to both local and global understanding of glacier sensitivity to changing ocean conditions.

487

Distribution and seasonal evolution of supraglacial lakes on Shackleton Ice Shelf, East Antarctica

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Supraglacial lakes (SGLs) enhance surface melting and can influence the structural integrity of ice shelves. However, the seasonal evolution of SGLs and their potential influence on ice shelf stability in East Antarctica remains poorly understood, despite high SGL densities on a number of potentially vulnerable ice shelves. Using optical satellite imagery, air temperature from climate reanalysis data and modelled melt predictions, we provide the first multi-decadal analysis (2000-2019) of seasonal SGL evolution on Shackleton Ice Shelf, Antarctica's northernmost remaining ice shelf which buttresses Denman Glacier. The ice shelf experiences locally high surface melt rates (>200 mm w.e. yr -1) and has the potential to support extensive melt ponding. In a typical melt season, we found hundreds of SGLs were, on average, 0.02 km2 in area, 0.9 m deep, and held a total meltwater volume of 5.9 x106 m3. At their most extensive, SGLs covered an area of 53.5 km2, but were clustered towards the grounding line, where densities approached 0.27 km2 per km2. Here, their development is linked to an albedo-lowering feedback associated with katabatic winds, the presence of blue ice and exposed rock. The SGLs drain supraglacially, through the ice, or refreeze at the end of the melt season. SGLs are more extensive and hold a greater volume of meltwater during years with warmer mean DJF near-surface temperatures and more short-lived, high magnitude modelled snowmelt events. Our analysis provides important constraints on the boundary conditions of supraglacial hydrology models and numerical simulations of ice shelf stability.

1387

Rapid transient response of Antarctic basal melt rates to changes in precipitation

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Ocean-driven melting of Antarctic ice shelves remains poorly understood and challenging to simulate, despite its importance for ice sheet stability and global sea level rise. As we seek to improve model representation of Antarctic melt, both over the historical period, and for future projections, we need to better understand how biases and uncertainty in forcing can affect the simulated ice shelf melt. In particular, climate models differ in the magnitude and spatial patterns of precipitation over the Southern Ocean and near the Antarctic coast. Biases in precipitation can have significant impact on the shelf water mass properties, sea ice production, convection and sub-ice shelf melt rates.

In this study, we examine the transient response of basal melt rates to precipitation, using a 5km-resolution pan-Antarctic ROMS configuration with thermodynamically coupled (static) ice-shelf cavities. We perform sensitivity experiments covering the spread of CMIP5 historical precipitation, by scaling a historical precipitation climatology derived from a climate model (ACCESS1.3 downscaled by MAR). These simulations provide insight on the processes governing the transient response of ocean properties, sea ice, and basal melt, as well as the timescales associated with these responses.

1686

Constraining sub-ice shelf channel evolution and melt rates in West Antarctic ice shelves

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Antarctic ice shelves buttress against the sea level rise contribution of the Antarctic Ice Sheet, but they are vulnerable to mass loss from surface and basal melt as well as the calving of icebergs. Sub-ice shelf melt channels (basal channels) have become a focus of ice shelf research due to their prevalence on ice shelves, and they have been associated with enhanced, localized basal melting as well as enhanced ice shelf fracturing. However, their short-term behavior and impact on ice shelf stability is largely unknown. We investigate basal channel evolution using a suite of high resolution surface elevation and ice thickness data. Estimating melt rates remains a challenge because current surface mass balance estimates do not resolve the spatial variability that has been observed above basal channels, and because the ice above basal channels may not be in hydrostatic equilibrium, so ice shelf thickness change cannot simply be calculated from surface elevation change. We work toward constraining the hydrostatic imbalance above basal channels in order to more accurately estimate thinning and melt rates. We observe a variety of evolutionary behaviors in our investigation of several West Antarctic ice shelves, including consistent channel position and size (no melt), active basal melt and ice shelf thinning at channels heads, and migration of channels toward western shear margins (indicating preferential melt on the western channel flanks). In general, unchanging channels and wide channels are more likely to be in hydrostatic equilibrium, making it easier to estimate basal melt rates in these channels

1369

Using structure-from-motion to produce ~55-year-old hypsometry changes for the Dotson and Crosson Ice Shelves from trimetrogon aerial imagery

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For the past ~25 years, research has shown that the Dotson and Crosson Ice Shelves have undergone considerable change in their thickness and strain field as the grounding lines of their tributary outlet glaciers (predominantly Smith and Kohler Glaciers) have been retreating. It is hypothesized that these changes are due to melt in the sub-shelf cavity by Circumpolar Deep Water, but some studies suggest dynamic thinning as another potential mechanism. Altimetry and optical satellite data observations reveal that the thinning and grounding line retreat has been relatively constant since the mid-1990s; however, since there are no published data of these parameters prior to 1990, the temporal extent of thinning and retreat is unknown. Numerical model results propose that the outlet glaciers were in a steady state prior to 1970, but without vertical and positional measurements from this time period, these projections have not been validated. To better conceptualize the pre-1990 state of the region and examine the pre-1970 configuration, we use trimetrogon aerial imagery collected in 1966-67 to generate ~55-year-old surface elevations using structure-from-motion processing techniques. We determine pre-1970 steady state from changes in elevation which are estimated by differencing the historical elevations with present-day surface heights and change rates. By extending the timeline of hypsometry for the Dotson and Crosson Ice Shelves, we improve our understanding of whether behavior of the last ~25 years is a discrete incident or part of a long-term phenomenon. Our aim is to improve the constraints necessary for enhanced predictive and hindcast modeling.

521

Coupling Antarctic Ice-shelf Basal Melting in an Earth System Model

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Freshwater flux from the Antarctic Ice Sheet, which predominantly occurs through ice shelf basal melting and iceberg calving, is one of the largest sources of uncertainty regarding sea-level rise in a changing climate. Yet these processes are generally poorly represented in current Earth System Models (ESMs). As a step towards full and dynamic ice sheet coupling in an ESM, the U.S. Department of Energy's Energy Exascale Earth System Model (E3SM) has the capability to simulate ocean circulation within static ice shelf cavities, which is used to calculate ice shelf basal melt rates. Here, we present results from global simulations using these capabilities, in both fully coupled (active ocean, sea-ice, atmosphere, and land) and partially coupled (active ocean/sea-ice with prescribed atmospheric forcing) configurations. We assess the sensitivity of the modeled melt rates to changes in the region's climate, including freshening on the continental shelf and shoaling of the thermocline, which may then allow warmer deep waters to intrude into the ice-shelf cavities, further increasing melting. We also show that ice-shelf meltwater feeds back onto the broader regional climate, for example, by affecting melting under neighboring ice shelves, sometimes dramatically so. We demonstrate that significant reductions in melt-rate biases can be achieved through modifications to ocean model mixing parameterizations in E3SM. We also see significant differences in the degree of interannual-to-decadal variability in melting between ice-shelves.

740

Temporal variability in basal melt rates on the Amery Ice Shelf

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The Amery Ice Shelf is the third largest ice shelf in Antarctica, draining approximately 16% of East Antarctica. The ice shelf has a very deep grounding line (~2500 m below sea level) driving locally high basal melt rates due to the pressure-dependence of the melt point of ice. Basal melt is highly variable on the shelf, including a large region of re-freezing along its western flank. Previous studies have indicated cyclonic ocean circulation beneath the ice shelf, with high salinity shelf water entering the ice shelf cavity in the east and outflow of ice shelf water and marine ice formation in the west. The heat content of the incoming shelf water can be highly variable on interannual timescales.

We present a multi-year, high-density timeseries of basal melt rates from the Amery Ice Shelf, collected using Autonomous phase-sensitive Radio-Echo Sounders (ApRES). Results are supported by independent measurements of basal melt derived from CryoSat-2 satellite data and a borehole-deployed acoustic Doppler current profiler (ADCP). These instrument datasets indicate that basal melt rates are highly variable on a range of timescales, indicating a complex ocean environment within the ice shelf cavity. We discuss what can be learned from our in situ measurements, and how they can be used to validate and improve oceanographic models, feeding into models of the glacier's future behaviour.

14

Turbulence Observations beneath the Larsen C Ice Shelf, Antarctica

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Antarctic ice shelves restrain the flow of grounded ice into the ocean, and are thus an important control on Antarctica's contribution to global sea level rise. Ice shelves interact with the ocean beneath them, and the transfer of heat through the ice shelf-ocean boundary layer is critical in setting the basal melt rate and the sub-ice shelf circulation. The physics of this boundary layer is poorly understood however, and its inadequate representation in numerical models is hampering our ability to predict the future evolution of Antarctic ice shelves and global sea-level rise. Using a hot-water drilled access hole, two turbulence instrument clusters were deployed beneath the southern Larsen C Ice Shelf in December 2011. Both instruments returned a year-long time series of turbulent velocity observations, providing a unique opportunity to explore the turbulent processes at two depths within the ice-ocean boundary layer. Our results show that although the scaling between the turbulent kinetic energy (TKE) dissipation rate and mean flow speed varies with distance from the ice shelf base, the TKE dissipation rate is balanced entirely by the rate of shear production. The freshwater released by basal melting plays no role in the TKE balance. Ultimately the aim of these observational efforts is to better constrain our parameterisations of the boundary layer in large-scale numerical models, allowing more accurate simulations of ice shelves to be made under the warming climate.

686

Constraining an ocean model under Getz Ice Shelf, Antarctica, using a gravity-derived bathymetry

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Getz Ice Shelf in West Antarctica is the largest producer of ice shelf meltwater in Antarctica, buttressing glaciers with enough ice to raise sea-level by 22cm. We present a new bathymetry of the Getz sub-ice shelf cavity using a three-dimensional inversion of airborne gravity data constrained by multibeam bathymetry data at sea and a reconstruction of the bed topography from mass conservation inland. The bathymetry is more than 500m deeper than previously estimated, with wider seafloor channels and a steeper transition with grounded ice. When incorporated into an ocean numerical model, the new bathymetry provides a better description of the spatial distribution of ice shelf melt, specifically along the grounding lines of the glaciers. While the melt intensity is overestimated due to a positive bias in ocean thermal forcing input, the study reveals the main pathways along which Circumpolar Deep Water enters the cavity and corroborates the observed rapid retreat of Berry Glacier along a deep, wide, retrograde channel.

587

A Structural Glaciological Analysis Reveals Ice Shelf Calving Regime Change

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Over the last two to three decades changes in the calving regimes of several Antarctic ice shelves have been observed. These changes have been found to be predominantly driven by alterations in atmospheric and/or oceanic conditions. Understanding the mechanisms responsible for ice shelf calving, as well as how these mechanisms interact and evolve, is key to predicting the vulnerability of Antarctic ice shelves to future calving regime change. Changes in the calving regimes of ice shelves can influence their buttressing potential, and ultimately, the throughput of mass to the ocean. We performed a structural glaciological analysis of changes in structures on the Sørsdal Glacier, East Antarctica, in order to identify the glacial features that drive calving. These features were investigated for their interaction and evolution using surface elevation data in conjunction with a time-series of satellite imagery. We identified the presence of rifts, surface and basal crevasses, as well as basal channels. A complicated relationship was found to exist between basal channel geometry and the other glacial features, where a change in basal channel shape influenced the propagation of basal crevasses and the formation of rifts, and hence the stable calving front position (due to rifts and basal crevasses being the primary drivers of calving). These findings indicate that the calving regime of the Sørsdal Glacier exhibited change without obvious oceanic or atmospheric drivers, suggesting that the calving regimes of Antarctic ice shelves are not static, even the ice shelves not experiencing noticeable changes due to global warming.

887

Breaking Better: including rifts in ice shelf models

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Through-cutting, laterally propagating rifts become the boundaries along which icebergs calve, thereby determining the position of the ice shelf front. Shelf front position, in turn, is both a forcing on and response to the conditions that drive ice shelves to change over time. Simulation of past and future ice shelf change thus requires some ability to represent rift propagation computationally. We are developing an approach to embed rifts explicitly in a computational ice flow model, and here we present validation studies using rifts in Ross Ice Shelf. We show that a linear elastic fracture mechanics approach explains their behaviour and that embedding rifts explicitly improves representation of shelf-wide stresses and rift propagation.

We use the extended finite element method to model rifts in elastic sub-domains on which we impose shelf-equivalent stress fields by calculating equivalent nodal forces. We have validated our routines using classic analytical test cases. The next step is to determine whether or not embedding rifts into a model improves its performance. Specifically, we examine the difference between simulations that use only 'far-field' glaciological stresses associated with ice shelf geometry and boundary conditions and simulations that embody both the far-field and the near-field effects of the rifts themselves. Real-world Ross Ice Shelf rifts and observational data sets are used for this purpose.

806

Terdiurnal tide rocks the Ekstroem Ice Shelf, Antarctica

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The floating ice shelves surrounding Antarctica stabilize the Antarctic ice sheet and link its ice masses to the dynamic ocean system. The periodic changes of the ocean tides force ice shelf dynamics, influence ice stream velocities, and therefore affect ice mass balance. GPS observations can directly measure changes in ice velocities, but internal causative processes within the ice body remain hidden. However, seismological measurements of ground motion reveal the stress state of ice bodies and hence can give clues about internal ice dynamics.

We analyzed seismological data from Neumayer Station III, Dronning Maud Land in East Antarctica, and calculated spectral noise levels using probability power spectral densities. The noise levels in the frequency range of 1-10 Hz change periodically with the ocean tides, but additionally to the major diurnal and semi-diurnal tidal constituents, we observe a strong terdiurnal component (8 hour period) in the noise levels reaching the same magnitude as semi-diurnal noise changes, although the amplitude of the exciting terdiurnal tide is only about a tenth of the semidiurnal amplitude. We speculate that a geometric resonance in shallow cavities near the grounding line might amplify the terdiurnal tide and reduce basal drag. Consequently the ice stream velocity increases and higher stress release leads to the observed elevated noise levels.

Linked ice shelf–ocean models therefore underestimate the influence of the terdiurnal tide and require additional processes to explain the strong effect it has on noise levels in seismological data and on the stress-state of the ice body.

959

Present and past evolution of Fimbul Ice Shelf region, East Antarctica: Ground-based investigations over three ice rises

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Ice rises are locally grounded features surrounded by floating ice shelves. They help regulate the outflow of ice from the Antarctic Ice Sheet, while holding past climate information within their ice stratigraphy. We investigate the present and past evolution of three ice rises located within Fimbul Ice Shelf in Dronning Maud Land, East Antarctica. These ice rises are within ~200 km of each other but differ in their settings within the ice shelf. Investigating their evolution thus allows extracting insights into the dynamics of this region and ice-rise evolution. We use ground-based geophysical measurements including static and kinematic GNSS, firn cores and ice-penetrating radars to determine their glaciological settings including surface and bed topography and surface flow speeds. Surface mass balance estimates show strong upwind-downwind contrast, a sign of orographic precipitation on all the ice rises. Mass balance using Input-Output Method show Blåskimen Island to be thickening at ~0.3 mi.e. yr-1 while initial estimates from other two ice rises show Kupol Moskovskij to be thickening (~0.4 mi.e. yr-1) and Kupol Ciolkovskogo close to balance (~0.1 mi.e. yr-1). Presence of distinct englacial features in the ice stratigraphy suggests stable divide positions for at least 500—1100 years for the three ice rises. To investigate longer-term evolution, we apply a thermo-mechanically coupled Elmer/ICE model to profiles going across these ice rises and constrain the model results with present-day flow speeds and englacial stratigraphy. Here we present a synthesis of our results and discuss the emerging picture of the dynamics of this region.

1100

Mapping coastal ice in Victoria Land by interferometric SAR and laser altimetry

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The Victoria Land coast is a unique environment containing a mixture of open water, floating ice tongues, icebergs, sea ice and landfast ice. The abundance and variability of the ice attached to the Antarctic coast is a consequence of oceanic, atmospheric, and glaciological processes, including coastal currents, ice shelf melting and supercooling and wind patterns. Our hypothesis is that the stability of ice tongues is a result of such interactions. In this study we investigate seasonal patterns in fast ice and relate these to ice tongue dynamics. In order to establish such a relationship a time series of landfast ice extent and deformation is assessed.

We map fast ice extent over regions of the Victoria Land Coast in the Western Ross Sea, from 2017 to 2019 using SAR interferometry. This method has been successfully tested in the Arctic (e.g. Dammann et al., 2019) for fast ice with relatively small deformation and showing strong radar phase coherence. We use Sentinel -1 in image (IW) mode with a 12 day repeat pass orbit image pairs. Sentinel-1 has been in operation since 2016 enabling the development of a 4 year InSAR time series showing fast ice extent and deformational patterns. In addition, ICESat-2 elevation data reveal freeboard and allow estimation of fast ice thickness. We present preliminary results of how fast ice deformation is related to its thickness. By extending the InSAR time series the next steps will be to establish a relationship between ice tongue dynamics and landfast ice morphology.

84

Regional modelling of the atmosphere, ocean and ice sheets over Antarctica and the Southern Ocean

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The climate dynamics at high southern latitudes is controlled by strong interactions between the atmosphere, the ocean and the ice sheets. In order to study the role of those exchanges in the variability and the predictability of the system, a new regional model is currently developed. The configuration covering the Southern Ocean south of 30°S is based on the atmospheric model COSMO-CLM, the sea ice ocean model NEMO-LIM and the ice sheet model f.ETISh. The distribution of key variables such as sea ice extent, wind stress and simulated fluxes at the ice shelves base are evaluated in a 1-year simulation with the model by a comparison with observations as well as with the results of multi-decadal uncoupled or partly coupled simulations (in particular with the coupled ocean ice-sheet model). The goal is to describe the main biases and identify their origin in order to reduce them in the forthcoming simulations with this fully coupled regional model.

497

Acceleration of ocean-driven glacial melt in Amundsen Sea Embayment, West Antarctica, measured using stable seawater isotopes

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The West Antarctic Ice Sheet (WAIS) contains enough water to increase global sea level by 3.3m. 200,000km² of WAIS are drained by the fast-melting Pine Island Glacier via a floating terminus into Pine Island Bay, in the Amundsen Sea Embayment. The mass balance of West Antarctica is dominated by dynamic losses in the Amundsen Sea Embayment, where glaciers are grounded on reverse-sloping beds, as deep as 2500m below sea level. This mass loss is mostly driven by basal melting, where warm subsurface circumpolar deep water (CDW) comes into contact with ice shelves at grounding zones. Remote sensing techniques approximate mass loss based on elevation timeseries, but cannot account for losses via calving, or subglacial meltwater rivers flowing into the ocean. Here, we present a timeseries of meltwater measurements using 670 paired stable isotopes-salinity samples from Pine Island Bay during Austral summer in 2007, 2009, 2014, and 2019. Glacial ice is extremely depleted in two stable isotopes - δ18O and δD – these isotopes can be used, along with salinity, to calculate the fraction of glacial meltwater in coastal seas from all meltwater sources. This method directly measures meltwater presence, and is completely independent of other methods used to estimate melt. Measuring salinity and stable isotopes, a 40% increase in meltwater measured over the observation period, indicating an acceleration of melt by glaciers terminating in the Amundsen Sea Embayment, with implications for global sea level rise.

132

On the Link between the Southern Ocean Fronts and Antarctic Ice Shelves Thinning

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Improving our knowledge of ice shelf–ocean interactions is a critical step toward reducing uncertainty in future sea level rise projections. It is now evident that ocean–driven basal melt is the major cause of ice loss from Antarctica's fringing ice shelves. However much of the fundamental dynamics of how the ocean delivers heat to the ice shelves remains unresolved.
Progress in this area requires bringing together the fields of ice shelf–ocean interactions and large–scale Southern Ocean oceanography. One way forward is constraining the contribution of changes in Southern Ocean circulation to the recent acceleration in Antarctic Ice Sheet mass loss. Using a combination of data sets (altimetry, hydrography and ice shelf thinning estimates), we document the variability of the CDW properties (upwelling location, temperature and salinity) and its link to Antarctic ice shelves' thinning rates. Observations show that changes in the thermohaline properties of CDW over the last 20 years are consistent with a southward shift of warm CDW towards the Antarctic continent. Our results also show that the areas where CDW upwells closer to the continental break coincide with the regions where Antarctic ice shelves are melting the fastest, especially in East Antarctica. East Antarctica has long been thought to be a stable part of Antarctica. However, our results suggest East Antarctica is more vulnerable to ocean forcing changes than previously thought.

282

Automatically Extracted Antarctic Coastline Using Remotely-Sensed Data: An Update

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The temporal and spatial variability of the Antarctic coastline is a clear indicator of change in extent and mass balance of ice sheets and shelves. In this study, the Canny edge detector was utilized to automatically extract high-resolution information of the Antarctic coastline for 2005, 2010, and 2017, based on optical and microwave satellite data. Visual comparisons have been conducted, and the accuracy of planimetric position of automated extraction is better than two pixels of Landsat images (30 m resolution). Our study shows that the percentage of deviation (<100 m) between automatically and manually extracted coastlines in nine areas around the Antarctica is 92.32%, and the mean deviation is 38.15 m. Our results reveal that the length of coastline around Antarctica increased from 35,114 km in 2005 to 35,281 km in 2010, and again to 35,672 km in 2017. Meanwhile, the total area of the Antarctica varied slightly from 1.3618 × 107 km2 (2005) to 1.3537 × 107 km2 (2010) and 1.3657 × 107 km2 (2017).The results indicated that the decline of the Antarctic area between 2005 and 2010 is related to the breakup of some individual ice shelves, mainly in the Antarctic Peninsula and off East Antarctica. We present a detailed analysis of the temporal and spatial change of coastline and area change for the six ice shelves that exhibited the largest change in the last decade. The largest area change (a loss of 4836 km2) occurred at the Wilkins Ice Shelf between 2005 and 2010.

1485

Beryllium isotope fractionation in Antarctic marine sediments

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Be isotopes from the authigenic phase of Antarctic marine sediment are being applied to understand past and present ice shelf and ice sheet dynamics. However, the geochemical behavior, sourcing and transport pathways of Be isotopes, namely ^{9}Be and meteoric ^{10}Be, in the Antarctic marine environment is still poorly understood, making the interpretation of isotopic concentrations and ratios with respect to paleoenvironmental and paleoclimate changes in sediment archives challenging. Further, geochemical extraction procedures for Be isotopes within the authigenic phase is complex due to its affinity to different minerals with variable degrees of binding strength. In open ocean, coastal or temperate riverine environments several chemical leaching procedures have been proven to be reproducible and conservative, however they have yet to be validated in polar regions. We apply a range of single and sequential extraction procedures on marine sediments from the front of the Amery Ice Shelf to ascertain the chemical phases that Be isotopes are associated with. We find that, as in the previous studies, both ^{9}Be and ^{10}Be are primarily associated with the labile oxide phases. However, unlike more temperate regions, $^{10}Be/^{9}Be$ ratios vary with strength of the extraction technique applied, and the amount of Fe and Mn oxide phases dissolved. Comparing the different extraction techniques has provided an opportunity to assess their efficiency in targeting different Be bearing phases, which will aid in our ability to selectively extract the authigenic Be isotopes, while avoiding the component which may have been delivered in reworked basal sediments of terrigenous origin.

1442

Responses of Antarctic melting to the future climate forcings

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The impact of forcings from CMIP5 CGCMs on the future projections of regional ice sheet melting and sea level rise produced by ice sheet model is investigated. The 2-dimensional (2-D) shallow shelf approximation model (MacAyeal, 1989), which is implemented in the Ice Sheet System model (ISSM) (Larour et al., 2012) is used. The historical runs and future projections forced by changes in atmospheric and oceanic forcings based on IPCC RCP(Representative Concentration Pathway) scenarios from climate models are carried out. From 1950 to 2100, ensemble experiments with atmospheric forcing-only, oceanic-forcing only, and all forcings from RCP2.6, RCP4.5, RCP6.0 and RCP 8.5 scenarios are conducted, respectively, to investigate the relative impact of forcings. The changes in ice velocity and ice thickness are analyzed and relative impacts of atmospheric and oceanic forcings on future changes are estimated. The global and regional implication of these changes are also investigated.

714

Airborne and ground-based geophysical evaluation of the englacial hydrological system near the grounding zone of the Sørsdal Glacier, East Antarctica

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Large swathes of the margin of the East Antarctic Ice Sheet experience surface melting during the austral summer. The nature and temporal evolution of the englacial hydrological system is poorly known, however, as are its potential connections with subglacial water systems and their effects on ice dynamics. We acquired helicopter-borne and surface-based ground-penetrating radar (GPR), broadband and high-frequency passive seismic and electrical self-potential (SP) data to delineate the geometry and monitor the temporal evolution of the englacial hydrological system near the grounding zone of the marine-terminating Sørsdal Glacier, Princess Elizabeth Land, East Antarctica. Our data, acquired between the austral summers of 2016-17 and 2018-19, reveal the presence of shallow englacial drainage structures interconnected with several surface lakes and with each other over minimum englacial distances of several kilometres. This englacial hydrological system, likely confined to within ~ 20 m of the glacier surface, surprisingly appears to be active not only through the austral summer but also throughout the Antarctic winter. Here we discuss the system's spatial and temporal drainage characteristics and their inferred forcing by meteorological effects and ocean-tide impacted ice dynamics. Our observations and inferences have important implications for the volume and timing of meltwater runoff and contribution to the surface mass balance of East Antarctica's ice margins.

950

Interannual-to-multidecadal responses of Antarctic ice shelf-ocean interaction and coastal water masses during the 20th century and the early 21st century to dynamic and thermodynamic forcing

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Much attention has been paid to ocean-cryosphere interactions over the Southern Ocean. Basal melting of Antarctic ice shelves has been reported to be the primary ablation process for the Antarctic ice sheets. Warm waters on the continental shelf, such as Circumpolar Deep Water (CDW) across the shelf break and Antarctic Surface Water (AASW) warmed up in summer, play a critical role in active ice shelf basal melting. However, the temporal evolution and mechanisms of the basal melting and warm water intrusions throughout the 20th century and the early 21st century have not been rigorously examined and are not fully understood. Here, we conduct a numerical experiment of an ocean-sea ice-ice shelf model forced with a century-long atmospheric reanalysis for the period 1900–2010 to examine the interannual-to-multidecadal variability in the Antarctic ice shelf basal melting and the role of coastal water masses. The modeled Antarctic ice shelf basal melting has gradually increased about 1.5-fold from 700 Gt/yr to 1100 Gt/yr over the study period. A series of numerical experiments demonstrate that changes in wind stress over the Southern Ocean drive enhanced poleward heat transport by stronger subpolar gyres and reduce coastal sea-ice and cold-water formations, both of which result in an increased ocean heat flux into Antarctic ice shelf cavities. Furthermore, an increase of sea-ice free days leads to enhanced regional AASW contribution to the basal melting. This study demonstrates that changes in Antarctic coastal water masses are key metrics for better understanding of the ocean-cryosphere interaction over the Southern Ocean.

988

40 Years of Föhn Wind-Induced Melt on the Antarctic Peninsula from 1979-2018

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Warm and dry föhn winds on the lee side of the Antarctic Peninsula (AP) mountain range cause surface melt that can destabilize vulnerable ice shelves. Topographic funneling of these downslope winds through mountain passes and canyons can produce localized wind-induced melt that is difficult to quantify without direct measurements. Our Föhn Detection Algorithm (FonDA) identifies the surface föhn signature that causes melt using data from twelve Automatic Weather Stations on the AP and uses machine learning to detect föhn in 5km Regional Atmospheric Climate Model 2 (RACMO2.3p2) output and in the ERA5 reanalysis. We estimate the climatology and impact of föhns that cause surface melt on the AP surface energy budget, surface melt pattern, and melt quantity from 1979-2018. We show that föhn-induced melt is strongest at the eastern base of the AP and the northern portion of the Larsen C ice shelf, and can occur on the Ronne ice shelf, farther south than any previous research has indicated. We identify previously unknown wind-induced melt possibly katabatic in nature on the Wilkins and George VI ice shelves. The observed warming and associated southward shift of westerly winds on the AP suggest the possibility of concomitant increases in wind-induced melt. Interestingly, neither RACMO2 nor ERA5 datasets exhibit a significant increase in föhn melt over the past 40 years.

503

Icefin observes super cooling and marine ice accretion in a basal crevasse beneath Ross Ice Shelf

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In December 2019 we deployed the remotely operated underwater vehicle (ROV) Icefin 3-4 km seaward of Ross Ice Shelf grounding zone. During our final mission we drove into a 50 m tall basal crevasse and found a transition from melting meteoric ice to accreting marine ice from the base to the top. The accreted ice demonstrated a vertical gradient of crystalline textures and color, and the surrounding waters in the top 10 m of the crevasse were supercooled. We interpret this to be evidence of in situ ice pumping with implications for ice-ocean interactions, shelf stability, radar interpretation, and ecosystem processes.

In total, we completed 5 km of survey transects over three missions in the 30 m thick ocean cavity below 585 m of ice at Kamb Ice Stream grounding zone. We also observed a stratified water column with maximum thermal driving of +0.3°C, melting meteoric and sediment-laden accreted ice, five 40-50 m tall crevasses over a 1.5 km along-flow transect, and possible sediment wedges on the seafloor. ROV Icefin was developed in the Planetary Habitability and Technology lab (Meister et al., 2018) specifically for borehole and under-ice deployments and carries multiple sonars, cameras, and biogeochemical sensors. The observations presented here are the result of collaboration with NZ Antarctic Science Platform and the NZARI Ross Ice Shelf Programme at KIS-1 camp.

622

On the Tidal Currents Observed by Moorings in Prydz Bay, East Antarctica

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We firstly report on mooring observations of tidal currents in Prydz Bay, East Antarctica. The observed tidal currents are mixed diurnal-semidiurnal, with the spatial and temporal averaged value of 2.58 cm s-1 for all the current meter observations over the continental shelf. Probably steered by the topography, the major axes of the tidal ellipses are generally aligned south-north, and the tidal phases are modulated by both the baroclinic and barotropic tidal components. At the Amery Ice Shelf calving front, the averaged tidal kinetic energy can account for a fraction of ~13% with respect to the total kinetic energy during the observing period. Although the long-term average tidal heat flux across the Amery Ice Shelf front is negligible, the ratio of the tidal heat flux standard deviation to the residual heat flux standard deviation can be up to 41%. For better understanding the tidal influences on the Amery Ice Shelf basal mass balance, we also assessed the temperature and salinity records from six boreholes drilled through the Amery Ice Shelf. We identified tide-like pulsing from the potential temperature and salinity record from the sub-ice-shelf cavity, implying the remarkable tidal influences in the ice-ocean boundary layer. Both the mooring and borehole data support that the tidal processes should be highlighted in the investigations of the interaction between the Amery Ice Shelf and the ocean.

1334

Looking for water on a small Antarctic Peninsula ice shelf

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Over the last two decades, several ice shelves in the Antarctic Peninsula region have experienced significant volume loss or even total collapse driven by atmospheric, oceanic and hydrological processes. The underlying premise of this study is to understand the role of liquid water in the modification of the mechanical properties of ice shelves that may lead to destabilisation. This presentation will focus on the first stages of a wider field and modelling programme based on the Müller Ice Shelf in which we will present the stratigraphic characterisation of three ice cores, observations of the drainage system and the first steps towards drainage system modelling.

During the initial field campaign (February 2019), no liquid water was observed at the surface, however, during the drilling of the three firn cores, liquid water was present at all sites. The three cores where taken with an electrical drill, and two reached approximately 18 m depth, and the third 4 m. Depths where limited by the presence of completely saturated material which prevented further extraction. On analysis in the laboratory, the conductivity of the saturated sections was found to be equivalent to freshwater therein confirming the presence of aquifers within the firn. The prevalence of water and the characterization of the aquifers will provide a baseline for future dynamical studies using physically based models.

673

A boundary layer framework to explore the physics of ice-ocean interactions

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Ocean-driven melting at the bottom of ice shelves is a primary cause of mass loss in present-day Antarctica. However, direct observations of the ice-ocean boundary remain sparse and challenging to date. This on one hand leads to a limited understanding of the physical processes at work at the ice-ocean interface, while on the other hand little consensus exists as to whether the parameterizations commonly employed in ice sheet simulation codes and ocean models are physically realistic. In this work we pursue a different approach, and seek to derive a self-consistent, first-principle model of the ice-ocean boundary layer. Building off an analogy with the planetary boundary layer, we construct a boundary layer model describing a buoyancy-driven current originated by the contact of warm ocean water with the ice shelf bottom, and its evolution along the shelf. Within this framework, we investigate two distinct regimes: the first one is alike katabatic layers in the atmosphere, with the key difference that adiabatic heating is here replaced by heat advection along the shelf; the second regime is an analogue to Ekman layers, with rotation effects playing a dominant role. We conclude by discussing the role of eddy viscosity closures, and particularly the importance of including the effects of stratification on turbulent mixing in models of the ice-ocean boundary layer.

Low precipitation and high temperature recorded in Bahía del Diablo glacier, Antarctic Peninsula

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During the period 2015-2019 annual precipitation observed in Bahía del Diablo Glacier, northeastern Antarctic Peninsula, was very low compared with previous years (2003-2014). Annual water equivalent precipitation measurements at sea level and at 650 m a.s.l. are obtained every year in the nearby area of the glacier. An automatic weather station also nearby the glacier recorded high mean air summer temperatures during this period. In consequence, both effects led to a very negative mass balances for Bahía del Diablo glacier after having a series of positive or near zero mass balances. Precipitation nearby the glacier was ~150 mm w. e. less than the mean during the previous period of 12 years. At sea level the precipitation recorded was ~50% of the previous period, while at 650 m a.s.l. the recorded value was ~70%. This pattern of low precipitation was also recorded in the region at Marambio Station, where similar devices to the installed in Bahía del Diablo glacier were used to measure the annual precipitation. In particular, air temperature was high during January and February 2020 and the record of temperature of 18.3°C was recorded in Esperanza Station, near Bahía del Diablo glacier. This led to have very wet snow and surface rivers on the glacier surface, even at more than 500 m a.s.l, where usually there is only snow.

750

Surf's up! Sea Ice Loss and Ocean Swell as a Trigger for Antarctic Ice Shelf Disintegrations

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Understanding the causes of catastrophic recent disintegrations of Antarctic ice shelves (Larsen A and B and Wilkins) is crucial to improving models of the Antarctic ice-sheet system and assessing the vulnerability of remaining ice shelves to environmental change. This in turn is a key step to enabling more accurate prediction of the future ice-sheet state and its contribution to sea-level rise. While progress has been made towards understanding melt-related and glaciological processes that precondition and weaken the shelves, the mechanisms responsible for triggering their disintegration have remained largely unknown. Here, we examine a climate-related causal factor and trigger mechanism that has been overlooked to date – namely regional sea-ice loss (both pack and fast ice). Based upon analysis of satellite, wave-hindcast and model-output data, we propose that increased seasonal absence of a protective sea-ice "buffer" offshore exposed the vulnerable outer ice-shelf margins to increased flexure by ocean swells. Over time, this weakened existing outer-margin crevasse and rift systems to the point of calving of elongated outer bergs, which precipitated abrupt and rapid runaway disintegration of the larger ice-shelf areas weakened (preconditioned) by combined surface flooding and hydrofracture, thinning and glaciological factors. These are "common essential prerequisites" for disintegration in the cases examined. The new findings highlight sea-ice change/variability as an important additional player affecting ice-shelf stability, depending on the region and ice shelf. They also underline the highly-coupled nature of the ice-shelf system undergoing change, and the need to better understand, quantify and model the sea ice-ice sheet interactions involved.

867

India-Norway joint efforts to examine mass balance, dynamics, and climate of the central Dronning Maud Land coast, East Antarctica

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India-Norway joint project MADICE has conducted three field campaigns from Maitri Station to Nivlisen Ice Shelf and two promontory ice rises bounding the ice shelf. Radar and GNSS profiling revealed topographic characteristics and englacial ice stratigraphy. Both ice rises have distinct Raymond Arches, indicating sustained divide flow from ice rise's summits in the past few millennia. Three ice cores drilled at these summits were used to date radar reflectors in the top ~30 m and to map SMB over the past three decades. We found that regional climate models replicate SMB very well over the ice shelf, despite a large model-cell size (5-10 km). However, SMB over ice rises are hardly resolved with the models, probably due to complicated topography not well represented in the model. Phase-sensitive radar was used to measure vertical strain rates over ice rises and basal melting rates over the ice shelf. We found that the seasonality in basal melt rates near the calving front is caused by summer-warmed ocean surface water pushed by wind beneath the ice shelf front. A different melt regime was found further inland, where basal melt is much smaller, nearly uniform regardless of the season but largely correlated with tidal cycles. We are currently analyzing phase-sensitive radar data over ice rises to constrain flow law parameters so that Raymond Arches can be unequivocally interpreted using ice-flow models in terms of evolution of the ice rises, and eventually infer histories of regional mass balance.

971

Highly temporally and spatially variable Antarctic Ice Discharge throughout the 21st century.

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It has been widely reported that ice discharge from the Antarctic Ice Sheet has increased over the preceding decades. The vast majority of these increases can be attributed to the ongoing destabilization of the Amundsen Sea sector in West Antarctica, with limited change in East Antarctica. However, much less attention has been focused on the temporal and spatial variations of ice discharge in Antarctica over the observational period.

In this study we combine existing velocity products to create 12 timestamped velocity mosaics between 1999 and 2018 to investigate both overall trends in ice discharge and the variability across the observational period. At an ice sheet scale we report a 50 GT yr^1 increase in ice discharge in West Antarctica and no overall change in East Antarctica. However, at an individual catchment scale we observe considerable temporal and spatial variability. For West Antarctica, despite the overall increase in discharge clear periods of deceleration are observed in most individual catchments. In East Antarctica, despite overall consistency, 3-10% variations in ice discharge are observed at several major outlet glaciers (e.g. Denman, Totten, Frost, Cook, Matusevitch, Rennick). These variations in discharge are primarily controlled by the ocean, but are also strongly influenced by localized factors such as stochastic calving, fast ice induced calving events/advance, bed topography and pinning points; and in some cases resulting in opposing trends in neighbouring catchments. Improving our understanding the processes driving these short term variations will be important in improving the accuracy of future sea level contributions from Antarctica.

972

Links between calving dynamics, ice velocity and grounding line retreat of Denman Glacier, East Antarctica 1962-2018

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Over the past two decades outlet glaciers in Wilkes Land, East Antarctica, have been thinning, losing mass and retreating. This has raised concerns over the future stability of some of its major outlets that drain the Aurora Subglacial Basin, such as Totten, Denman, Moscow University and Vanderford Glaciers. Their present-day grounding lines are close to retrograde bed-slopes and, furthermore, geological evidence indicates that they may have experienced substantial retreat under past warm climates, which are similar to those predicted in the near-future. After Totten, Denman Glacier, is thought to be the largest contributor to global sea level rise in East Antarctica. However, despite its importance there are few detailed observations of its recent dynamics. In this study, we use remote sensing observations to report on the changes in glacier velocity (1962-2018), calving dynamics (1962-2018) and groundling line position (1996-2018). This reveals a ~17% increase in velocity between 1972-74 and 2018, and a retreat of the grounding line between 1996 and 2018. We also observe significant differences between Denman's present-day calving regime (1985-present) compared to past calving activity (1940s – 1985). In addition, Denman's ice shelf has shifted a few kilometres westward and now makes significantly less contact with an eastern pinning point that may have previously exerted a buttressing effect. Using a numerical ice flow model (Úa), we simulate these observed changes to explore the drivers of the recent acceleration.

35

Study of the Lange Glacier and the Impact Due to Climate Change in Admiralty Bay, King George Island, Antarctic Peninsula

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The Antarctic Peninsula and adjacent islands are areas where the greatest regional warming of the Southern Hemisphere has been identified. In order to characterize the implications of Southern warming, we selected the Lange Glacier (LG) on King George Island, to assess: 1) superficial temperature and glacier dynamic using data loggers installed in stakes; 2) water conditions by a bathymetric survey and 29 CTD stations in front of the LG; 3) glacier front (GF) using both bathymetric and a Digital-Elevation-Model (DEM) data; 4) GF velocity using movement stakes data; 5) change in GF position using DEM and historical data of width GF; and 6) the calving flux (QC). Our results showed that 85% of the temperatures were above the 0°C melting point (mean=5.0±5.2°C). The stakes showed an average ice loss of 9.3±1.3cm. The mean glacier movement registered by stakes was 8.8±1.5m in the southeast direction (0.40±0.70m/day). This movement was corroborated by Sentinel-1 satellite images (Offset Tracking=0.43±0.01m/day). Bathymetric survey recorded depths from 10 to 220m at the GF, which corresponds to ice thickness below sea level. External waters intrusion to the Lange bay was identified from the oceanographic stations. The external water is warmer than resident waters, destabilizing the water column through convection processes. Our findings together indicated a continuous glacier fusion that increases its dynamics due to the increase of temperature, with a contribution of freshwater to the Admiralty Bay. Systematic monitoring is required to establish the direct implications of the LG climate change and water contributions to sea-level rise.

623

Sensitivity study of a Convective-melt parameterization into ROMS (Regional Ocean Modelling System)

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Recent laboratory-scale experiments and turbulence resolving numerical simulations have highlighted the importance of the convective processes on the ice-loss rate at the ice-ocean interface. Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) at the ice-ocean boundary indicated that, below a threshold ambient current the ice-ocean boundary layer is convectively driven and the meltrate is controlled by the thermal driving, rather than the strength of the ambient current. DNS under a sloping ice-interface have also shown that under such conditions, local stratification can suppress the turbulent transport at the ice-ocean interface (Mondal et al; 2019) and the future evolution of the ice-shelf is sensitive to the ice-shelf morphology. These results have been implemented into ROMS-MISOMIP as a modified ice-ocean scheme where a Heaviside function flips between convectively driven and shear driven melt parameterization, subjected to the ambient current. Sensitivity studies have been carried out over an idealized domain with varying thermal forcing as well as adding steps like ice-bathymetry. However, all the simulations generate unrealistic overturn-circulation inside the ice cavity and melting at the ice-interface effective controlled by the stronger shear leaving the convective melt parametrization obsolete. We speculate that an uncoupled sub-grid scale buoyancy forcing might create instabilities into the momentum field, followed by a faster transition into the velocity dependent melt-regime with higher ambient velocity.

519

Sensitivity of the Amundsen Sea Embayment to changes in external forcings using automatic differentiation

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Thwaites and Pine Island Glacier have been changing dramatically over the past decades. There is broad agreement that the intrusion of warm water into sub-ice shelf cavities is the primary driver of these changes but it remains unclear where these ice shelves are most sensitive to melt, and whether other processes could cause further or more dramatic mass loss. Here, we analyze the sensitivity of two high-resolution ice sheet models (STREAMICE and ISSM) to changes in boundary conditions and external forcing. We rely on automatic differentiation to derive the sensitivity of the volume above floatation after 3 years of simulation to changes in ocean-induced melt, ice rate-factor, basal friction, and surface mass balance. The sensitivity maps highlight the regions that are most at risk to changes in any of these forcings at high-resolution. We find that changes in basal melt close to the grounding lines or along shear margins have a large impact on the final volume above floatation. The sensitivity of the model to basal friction is large close to the grounding line of Pine Island glacier but limited in other regions. If the sensitivity to changes in the rate factor is significant along the shear margins of Pine Island, it is close to zero over the margins of Thwaites glacier, which calls into question a hypothesis that is frequently invoked in the literature. This exercise highlights the regions that are most at risk to changes in external forcings, but also which process should be properly captured by models.

1556

The strengths and weaknesses of the Thwaites Eastern Ice Shelf

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The Thwaites Glacier is one of the fastest changing glaciers and is likely to be a large contributors to sea level rise in the next century. It is 120km wide at its grounding line. Two thirds of the glacier flows more than 6m/day into a tongue of ice that has undergone significant changes in the last two decades, including two major retreats in 2002 and 2012. The other third of the glacier flows at 2m/day into a relatively stable Eastern Ice Shelf, maintained by the buttressing from a linear bedrock ridge roughly 40km from the grounding zone. Despite relatively stability, this ice shelf is also undergoing important changes. It's collapse could trigger glacier acceleration resulting in marked sea level rise.

As part of the International Thwaites Glacier Collaboration, the TARSAN Project has collected and analyzed oceanographic and glaciological data to identify and assess the evolving strengths and weaknesses of the Thwaites Eastern Ice Shelf.

Here we discuss the first findings from our analysis. Weaknesses include shear zones and rifting induced by the loss of the ice tongue; migrating basal channels; high localized basal melt rates; advected crevassed zones; and multiple pathways for circumpolar deep water to enter the subglacial cavity. These weaknesses are countered by strengths including the lateral extent of the bedrock ridge providing buttressing; relatively uniform and crevasse-free central ice shelf with a cold-ice core; and high accumulation of snow. Despite these strengths, the ice shelf is on a trajectory to collapse; however, we cannot say how soon.

466

Setting up a regional ocean model of the Ross Sea with the MIT general circulation model: validation and preliminary results from a Last Glacial Maximum paleo run

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Little is known about the oceanic circulation below ice shelves, yet this is a key aspect to be studied to better constrain Antarctic ice sheet sensitivity to past and projected climatic changes. During the last deglaciation (last 20'000 years), the impact that ocean circulation had on ice sheets and vice-versa is poorly understood, and the Ross Sea region stands out as a key place to study the present and past West Antarctic Ice Sheet dynamics.

We use a regional implementation of the MIT general circulation model for the Ross Sea to address this knowledge gap. The MITgcm allows circulation within ice shelves cavities, however in current implementation ice shelf geometry is fixed during runtime. Validation on present-day conditions is performed against the high resolution ocean reanalysis Mercator GLORYS and available data from Italian moorings.

We present preliminary results from a paleo-control run of the Last Glacial Maximum (LGM, 21'000 yrs ago). This simulation consists of a equilibrium spinup run started at the LGM, forced with PMIP3 simulated climatologies and bounded by a simulated LGM Antarctic ice sheet. Simulated circulation is compared with available geological proxies, and we assess the impact on the circulation of a reduced Ross Ice Shelf cavity during a glacial state.

1213

Spatial pattern of surface mass balance over the last three decades in the central dronning Maud Land Coast, East Antarctica

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The coastal region of Dronning Maud Land (DML), East Antarctica, is characterized by a large number of small ice shelves bound by isle- and promontory-type ice rises and rumples. These distinct topographic settings can make individual regions behave differently under ongoing climate change. To fill the knowledge gap in the central DML coast, we have conducted three field campaigns during Antarctic austral summers from 2016 to 2019, under an Indo-Norwegian research project MADICE on Nivlisen ice shelf and its fringing ice rises (Djupranen and Leningradkollen). We conducted shallow ice-penetrating radar sounding to see ice/firn stratigraphy in the top 30 m. In total five radar reflectors (isochrones) were tracked over a 400 km line covering the entire ice shelf and two adjacent ice rises. These isochronous reflectors were dated using two ice cores taken at the ice rise summits, with which the surface mass balance (SMB) history over multi periods in the past three decades was retrieved. The spatial SMB patterns of the Nivlisen ice shelf stayed similar for all periods over the ice shelf, small SMB in the eastern inlet of the ice shelf, and large SMB in the western end of the ice shelf. However, this east-west contrast and consequently the regional-mean SMB varied between periods. The SMB patterns over the ice rises are time variable and more complicated.
Keywords: Antarctic ice shelf, ice rises, ground-penetrating radar, ice core, and surface mass balance.

1622

The SOOS Amundsen and Bellingshausen Sector Working Group: current infrastructure and future perspectives

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The Southern Ocean Observing System (SOOS) is a joint initiative of the Scientific Committee on Antarctic Research and the Scientific Committee on Oceanic Research. The Amundsen and Bellingshausen Sea regional working group (RWG) is part of the newly formed RWG Consortium. This RWG aims to discuss progress and ideas in the Amundsen and Bellingshausen Sea sector to improve the functioning, development, outputs and outcomes of research, policy and stakeholder groups.
We present the outcomes of the first RWG meeting in Incheon, Korea (May 2019), and outline the objectives and key priorities for the coming decade in the Amundsen & Bellingshausen Sea sector. The workshop successfully outlined key drivers of the region and documented the status of multidisciplinary observations in the Amundsen/Bellingshausen Sector. From this consensus, the RWG identified key observational gaps, regional priorities, and challenges which will be presented here. The RWG aims to further collate a list of upcoming/anticipated work in the region to promote collaborative opportunities and to enable regional-scale observing, using SOOS best practice for observing systems. We will present how the community can engage and participate with the Regional Working Group and encourage further growth for the Amundsen/Bellingshausen Sea sectors in the future.

1625

Observations of a large anticyclonic eddy west of Thwaites Ice Tongue

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We present here the first observations of a large (30km) anticyclonic eddy west of Thwaites Ice Tongue. The TARSAN hydrographic cruise (Jan-Mar 2019), as part of the International Thwaites Glacier Collaboration, collected CTD and velocity data across the open Amundsen Sea shelf. As part of this survey, we identified a clear eddy feature in the habitually ice-covered region between Thwaites and Crosson.

The survey identified that the eddy circulated in the opposite direction to what would have been expected based on the local coastal current and bathymetry. The ship collected several ADCP and CTD transects across this feature and deployed an autonomous underwater glider in the centre. We describe the density and velocity structure, as well as related biogeochemical properties, of this eddy. We suggest a mechanism for the existence of this feature related to deep circulation of modified circumpolar deep water in the bathymetric channels which deliver warm water to the base of the Amundsen Sea embayment glaciers.

450

Change and variability in Antarctic coastal exposure (lack of sea ice offshore) since 1979

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Sea ice is a ubiquitous though seasonally-variable feature of the Antarctic coastal zone, where it interacts strongly with the floating ice sheet margins that are particularly vulnerable to changing ocean conditions (including warming). Indeed, there is also mounting evidence of potentially strong relationships between coastal sea ice distribution and the characteristics and stability of glacier tongues and ice shelves, suggesting that sea ice is an indirect (though poorly-understood) player in regulating sea-level rise (Nature, Massom et al., 2018). Here, we introduce and present findings from two complementary new algorithms designed to quantify broad-scale change and variability in Antarctic coastal exposure to more open-ocean conditions (lack of sea ice offshore), by exploiting the satellite passive microwave sea-ice concentration record dating back to 1979. These are: (1) an "Antarctic Coastal Exposure Index"; and (2) a more detailed “Coastal Exposure Length” method. Initial examination of temporal and spatial patterns of occurrence and trends for 1979-2017 shows that West Antarctic coastal regions are largely dominated by an increase in coastal exposure, particularly in the West Antarctic Peninsular region but also in the Amundsen Sea. In contrast, areas of increasing coastal exposure area confined to smaller pockets only in East Antarctica, with the general trend being towards decreasing coastal exposure. This is further characterised by a distinct westward progression around the region, largely in summer. The new algorithms and findings complement the more widely-used sea ice concentration, extent and seasonality time series and a new analysis on fast ice.

400

Quantification of a significant and persistent Ice Shelf Water plume in the Western Ross Sea

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The Victoria Land Coastal Current comprises a significant and consistent plume of Ice Shelf Water which is sourced within the Ross Ice Shelf cavity and flows northward through Western McMurdo Sound. Here we combine >1,800 full-depth CTD profiles collected over 40 years to define the spatial extent and physical characteristics of the plume at the end of winter – the period in which the vast majority of observations have been made. At the point that it exits the ice shelf cavity the plume is in-situ supercooled by up to 50 mK, with supercooling extinguished within ~100 km. From these data we estimate the rate of supercooling relief to new ice growth – onto either existing ice cover or crystals suspended in the flow – and the net freshwater flux to the Ross Sea. We examine possible sub-ice shelf pathways and processes of ice-ocean interaction to explain the observed characteristics, and hypothesise the ultimate source region of the meltwater. The three-dimensional structure indicated by the hydrography is in good agreement with recent spatial surveys of sub-ice platelet layer thickness and incorporated platelet ice. The general consistency of these combined indicators suggests little interannual variability of local circulation over the past four decades, despite long-term freshening and recent rebound of shelf water salinity in the Ross Sea.

1524

Preliminary analysis of ocean data from beneath Eastern Thwaites Ice Shelf

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As part of the International Thwaites Glacier Collaboration (ITGC) Thwaites - Amundsen Regional Survey and Network (TARSAN) project, two automated multi sensor stations were installed on the Eastern Thwaites Ice Shelf. The stations included an oceanographic instrumentation suite (CTDs, doppler current meters, and laser-stimulated fiber-optic thermal profiler, installed by hot-water drilling through the ice shelf into the ocean cavity below. Profiles of the ocean depth, salinity, and temperature indicate water characteristics consistent with Circumpolar Deep Water (CDW: 34.7 PSU, +1.05°C) for the lowest 200 meters of the 525 m water column, with a mixed layer above that is gradational between the CDW and so-called polar water. Doppler current motion indicates southwestward mean flow with eddies for the mixed layer, and slower less organized motion for the CDW layer. We compare the known regional ocean circulation and characteristics to present an observational ocean structure and circulation pattern.

1397

The Grounding Zone of Thwaites Glacier Explored by Icefin

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From January 9-12 2020, ROV Icefin conducted the first long range robotic exploration of the grounding zone of Thwaites Glacier, as part of the ITGC MELT project. Icefin, an underwater vehicle designed for borehole deployments, conducted 5 missions amassing over 15km of continuous data collection with ten sensors, including oceanographic sensors, imaging and bathymetric sonar. Missions extended seaward over 3.2km from the grounding zone where Icefin observed basal ice in a 0.5 m water column and seafloor contact. Imagery and sonar revealed a diverse set of basal ice conditions with complex geometry, including a range of terraced features, smooth ablated surfaces, crevasses, sediment rich layers of varying kinds, as well as interspersed clear, accreted freshwater ice. The water column ranged from ~100m thick downstream that thinned to an average of 50m before quickly narrowing in the last ~500m towards the grounding zone. Ocean conditions varied from moderately well-mixed near the grounding zone to highly stratified near the ice base at seaward locations. Generally subdued seafloor topography ran roughly parallel to ice flow direction. Sediments along the sea floor ranged from fine grained downstream to course angular gravel near the grounding zone distributed between larger boulders, and accreted basal ice contained heavy sediment load, often size sorted. Moreover, we catalogued organisms from the seafloor to the ice-ocean interface, including ice-burrowing anemones. Overall, the emerging perspective is that topography along the ice-ocean interface evolves dramatically from the grounding zone, and is influenced by the type of ice present in a given region.

1172

Annual Ice velocity mapping and mass balance of Antarctic ice sheet

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The knowledge of the ice flow is crucial for improving our understandings of a wide range of glaciological mass fluxes including ice-sheet mass balance, glacier physics, and glacier flow instability. we present a methodology which can automatically calibrate, mosaic, and post-process Landsat images into displacement maps, resulting in the new data products quantify the Antarctic continent-wide and seamless ice velocity. Specifically, we have assembled over 250,000 displacement maps to generate Antarctic-wide annual mosaics of ice velocity maps from more than 80,000 Landsat 8 images acquired between December 2013 and April 2019. We estimated the mass discharge of the Antarctic ice sheet in ~2008, 2014, and 2015 using the Landsat ice velocity maps, interferometric synthetic aperture radar (InSAR)-derived ice velocity maps (~2008) available from prior studies, and ice thickness data. An increased mass discharge (53±14 Gt yr-1) was found in the East Indian Ocean sector since 2008, due to unexpected widespread glacial acceleration in Wilkes Land, East Antarctica, while the other five oceanic sectors did not show significant changes. However, present-day increased mass loss was found by previous studies predominantly in west Antarctica and the Antarctic Peninsula. The newly discovered increased mass loss in Wilkes Land suggests that ocean heat flux may already be influencing ice dynamics in the marine-based sector of East Antarctic ice sheet (EAIS). The marine-based sector could adversely be impacted by ongoing warming in the Southern Ocean, which may be conducive to destabilization.

283

A spatio-temporal view of Western Ross Sea hydrography from the Ross Ice Shelf grounding line to the continental shelf-break

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The combined Ross Sea continental shelf and ice shelf cavity cross a latitudinal range from 85°S to 71°S. As well as normal oceanic complexities, oceanic flows through this domain encounter a range of unique processes such as polynya, sea ice growth and variability, the ice shelf-ocean interface and the mechanics of the cavity and grounding line. Due to the unique setting we must rely heavily on in situ observation to help with understanding and improved predictive capability. Here we synthesize recent hydrographic timeseries from a range of locations spanning from the Ross Ice Shelf cavity grounding line at around 83°S, though the cavity and cavity edge. Then we shift from cavity hydrography to polynya and coastal data and finally onto the continental shelf break. Much, but not all, of the data are contemporaneous and span more than a year. We compare this with existing hydrographic timeseries data on the Continental shelf. This allows identification of scales of cavity and continental shelf hydrography, seasonality and connectivity.

1187

The dynamic response of the Ross Ice Shelf to changes in pinning point configuration

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Ice rises and rumples, sites of localised ice shelf grounding, participate in shelf-wide mechanics by generating lateral and basal shear stresses. These stresses modify ice velocity and thickness, and in turn, may affect the dynamics of the grounding zone and tributary glaciers. The mechanics and dynamics of pinning point regulation of ice shelf flow are examined here with a case study on a collection of pinning points in the Ross Ice Shelf (RIS). A snap-shot force budget analysis of RIS pinning point mechanics provides context for a detailed examination of the ice shelf-ice stream system dynamics associated with the Shirase Coast Ice Rumples (SCIR) in the eastern RIS. A numerical model of RIS and tributary ice stream flow, with and without the SCIR, is used to quantify their contribution to resistive stresses in the system. This allows us to examine, in detail, how the pinning points modify stress budgets at the grounding line, the ways in which other sources of flow resistance can accommodate the loss of a pinning point, and some perhaps less intuitive effects associated with thickness gradients across the floating ice shelf. We find, for example, that MacAyeal Ice Stream located directly upstream of the SCIR is less responsive to the loss of the ice rumples than the obliquely oriented Bindschadler Ice Stream. These, and other, somewhat subtle effects in the coupled mass and momentum balances are, we argue, most easily revealed using a case study approach.

1670

Bathymetry under Antarctic ice shelves - a decade of progress from Operation IceBridge

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Bathymetry beneath ice shelves has been an elusive parameter for understanding the ocean-ice interactions controlling ice shelf stability. Community compilations of Antarctic topography demonstrate significant progress in measurements of thickness of grounded ice and acoustic bathymetry mapping from ships in open water. The connecting regions, just offshore from the present day grounding zone remain difficult to access, and can be mapped directly from geographically limited surveys using submersibles or seismic methods, or indirectly from airborne surveys.

Substantial international efforts have undertaken airborne surveys of the gravity anomalies over ice shelves in order to model the underlying seafloor bathymetry. Here we present an overview of the contributions from the NASA mission Operation IceBridge. Aerogravity inversions for bathymetry have been a vital component of the mapping efforts of Operation IceBridge, a ten year NASA mission flying a suite of aerogeophysical instruments over both the Arctic and Antarctic. Operating from South America, McMurdo Station and Hobart, Tasmania, Operation IceBridge has collected gravity data from ice shelves around much of the circumference of Antarctica. Together with other international efforts, these data reveal how circum-Antarctic sub-ice bathymetry mapping has been transformed over the last decade.

362

Influence of landfast sea ice on ocean-sea ice interactions in the area of the Totten Glacier, East Antarctica: a study with a high-resolution regional version of NEMO3.6-LIM3

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The Totten glacier drains over 570 000 km² of the East Antarctic ice sheet. Most of it comes from the Aurora Subglacial Basin and is marine based, making the region potentially vulnerable to rapid ice sheet collapse. Furthermore, over the past decade, the Totten glacier experienced net mass loss by surface lowering of its grounded part and thinning of its floating ice shelf. At broader temporal and spatial scales, understanding how changes in ocean circulation and thermodynamic properties are causing increased basal melt of Antarctic
ice shelves is crucial for predicting future sea level rise. In the context of the Belgian project PARAMOUR, we use a high resolution NEMO3.6-LIM3 regional model to investigate the climate's variability and predictability over the Totten area.

The focus here is on the role of landfast ice in the variability of the system. Landfast ice is sea ice that is fastened to either the coastline, the sea floor along shoals or grounded icebergs. Most sea ice models neglect or crudely represent the formation, maintenance and decay of coastal landfast ice. We parameterize landfast ice impact following the grounding scheme and tensile strength formulation of Lemieux et al. (2015, 2016), or by manually adding grounded icebergs over the continental shelf.

Those parametrizations are evaluated by comparing the simulated and observed extent of landfast ice. The impact of those parametrizations on the location and amount of sea ice and on the ocean circulation is then investigated to quantify the influence of landfast ice in the Totten area.

1295

Observed melt rate variability at the Totten Glacier Ice Shelf, East Antarctica

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The Totten Glacier drains a significant portion of the East Antarctic Ice Sheet. Satellite records have shown that the glacier has undergone thickness and velocity temporal changes, however, the drivers of these changes remain to be understood. Recent oceanographic observations near the Totten Glacier Ice Shelf front have found a pathway for deep warm water to enter the ice shelf cavity and potentially reach the grounding line.
To further explore the ocean's potential on modulating the Totten Glacier dynamics behavior, we deployed several autonomous phase-sensitive radio-echo sounders (ApRES) across the ice shelf and monitored basal melt rates within ~20 km of the grounding line for two years. Our results show a large spatial melt rate variability despite of the relative proximity of the sites. A numerical ocean model is used to give an insight to the potential causes of the observed melt rate variability.

782

Surface Melting in East Antarctica, a threat to ice sheet stability in a warming 21 Century climate!?

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Large parts of coastal East Antarctica show significant surface melting. The extend of melting varies from year to year. In some years, the surface of ice shelves like the Amery Ice Shelf is covered by kilometre long supra-glacial lakes. A supra-glacial hydrological network extends from upstream of the grounding line to the calving front. Supra-glacial meltwater in part refreezes at the surface and in crevasses at the end of summer and in part is draining into the ocean or the subglacial environment either in the form of rivers cascading across the calving front or through moulins into the sub-ice shelf cavity. Observed lake drainage events are in the order of a cubic kilometre, sufficient in size to have a significant impact on ice shelf cavity circulation and or subglacial drainage. Observations from the Antarctic Peninsula link supraglacial melting and melt ponding to ice shelf collapse and accelerated ice discharge through the removal of buttressing.
A review of the multidecadal record of supra-glacial melt distribution in East Antarctica with a focus on the Amery Ice Shelf is presented and its implication on Ice Sheet/Shelf Stability in a warming 21st Century Climate discussed.

853

Pathways and modification of warm water flowing beneath Thwaites ice shelf, West Antarctica

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Thwaites Glacier is a vulnerable and rapidly changing outlet for the West Antarctic Ice Sheet. Here we present the first direct observations of ocean temperature, salinity, and oxygen underneath Thwaites ice shelf collected by an autonomous underwater vehicle. These new observations indicate that deep water (> 800 m) underneath the central part of the ice shelf is in connection with Pine Island Bay, which would be a previously unknown westward branch of warm deep water entering the ice shelf cavity. For the first time it is also shown that warm water enters from the north in two troughs separated by a pinning point. The easternmost of these troughs has southward flow from surface to bottom towards the ice shelf cavity, while the westernmost has a northward flow of comparatively fresh and cold water near the surface and more southward components in the denser and warmer water nearer the seabed. Intermediate water masses were identified as warm deep water found north of Thwaites ice shelf that has been in contact with glacial ice. Spatial gradients of salinity, temperature and oxygen recorded underneath the ice shelf indicate that this is a previously unknown active area where several water masses meet and mixes. The central buttressing point is identified as a vulnerable region of change currently under attack by warm water inflow from all sides: a scenario that may lead to ungrounding and retreat more quickly than previously expected.

802

Bathymetry revised by hydrography observational data in Prydz Bay, East Antarctica

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Based on the International Bathymetric Chart of the Southern Ocean (IBCSO), we rebuilted an improved high resolution digital bathymetric model for the bathymetry of Prydz Bay and the surrounding region by compiling the water depths from in situ hydrography observations. After removing the reduplicated data from multiple data sets, we compared the water depths from the in situ hydrography observations with the seafloor depths from the IBCSO on the original IBCSO grid with a 500 m × 500 m spatial resolution. In the comparison, the data including multi-beam and single-beam echo soundings, digitized depths from nautical charts in IBCSO are fully preserved, and only the predicted bathymetry in IBCSO has been revised by the water depths from in situ hydrography observations with a specific gridding technique. Our bathymetry revision is mostly benefited by the observations from equipped seals, especially in the Amery depression. The improved digital bathymetric model can provide insights into the security of the voyages in Prydz Bay. In addition, by portraying an accurate seafloor around the continental shelf region, it favors our understanding of the dynamic and thermodynamic processes in the oceanic and sea ice circulation and the basal mass balance of the Amery Ice Shelf.

1720

Ice-ocean-ecosystem interactions influence CO2 uptake by a highly-productive coastal polynya

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Here we explore the potential impact of future climate-driven changes on the primary productivity and carbon dioxide (CO_2) uptake by Antarctica's greenest coastal polynya. With high primary productivity associated with the melting West Antarctic Ice Shelf, the Amundsen Sea Polynya (ASP) is a large sink for atmospheric CO_2 that is disproportionally important in its contribution to Southern Ocean air-sea CO_2 flux. Part of a classical high-nutrient/low-chlorophyl region, high productivity in these coastal seas may be explained partially by iron introduced from ice shelf melting, and the buoyancy-driven upwelling by the meltwater pump, but sea ice dynamics and winds are also important. Seasonal sea ice duration in the ASP is significantly reduced now compared to previous decades. High inter-annual variability in primary productivity suggests strong sensitivity to climate drivers. We explored how these physical drivers impact the coastal ecosystem using a 1-D numerical model developed for the ASP (Oliver et al. 2019). Model validation used the extensive observations from a field campaign in 2010-11 (ASPIRE; Yager et al., 2016). Productivity and carbon export were sensitive to potential future changes in sea ice cover, winds, and mixed layer depths. A continued decline of seasonal sea ice, increasing open water duration by up to 6 weeks, could lead to a reversal from net CO_2 uptake to net CO_2 outgassing for the ASP region.

24

Modulation of shelf water by ice-ocean interactions in Terra Nova Bay polynya, Antarctica

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Terra Nova Bay polynya (TNBP), located in a coastal region of the Western Ross Sea, is a latent heat polynya formed by persistent katabatic winds blowing from the Nansen Ice Shelf. TNBP is considered as a key region of High-Salinity Shelf Water (HSSW) formation by polynya operation. There also occur vigorous ice shelf-ocean interactions, so the HSSW can be modulated by the influence of meltwater flowing from the sub-shelf cavity. The product of mixing between HSSW and the meltwater is identified as Terra Nova Bay Ice Shelf Water (TISW). In this presentation, we investigate spatio-temporal variations of the TISW (potential temperature < –1.93 ℃) using the hydrographic observations (CTD/LADCP and Glider) in TNBP during 2014–2019. The TISW was formed in January and has been developed (colder and less saline) from February to March with a supply of super-cooled plume flowing out from the cavity region under the Nansen Ice Shelf. The plume mainly pumps out at 400–700 m depths along the left-hand side of the deepest valley as affected by Coriolis force. In March, the TISW was also observed around 50 km east from the Nansen Ice Shelf. In comparison with the historical results, the TISW becomes much colder (~ 0.1 ℃) now and its main outflow region seems to move from the Campbell Ice Tongue to the center of the Nansen Ice Shelf. We also discuss about "How does the TISW influence to seawater properties in TNBP?" using a simple 1-D model.

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