General Statement

Review of "*Seasonal resonance of diurnal coastal trapped waves in the southern Weddell Sea, Antarctica*" By S. Semper and E. Darelius

This paper is a comprehensive assessment of the seasonal variability of diurnal tidal currents in the southern Weddell Sea, using data from 29 moorings between 1968 and 2014. While the seasonal variability is known, and has been previously interpreted as response of diurnal tide-forced shelf waves to changing stratification and along-slope current (various papers from the 1980's), the increased data base and interpretation through sensitivity tests on an idealized model (Brink, 2006) makes this a valuable new study.

My specific comments are provided as margin comments and edits on the marked *.tex file. Most of these are relatively minor. Some major comments are as follows:

1. Lines 43-55, about CTWs, will possibly make no sense to a lot of readers without a dispersion curve to look at. Probably this means adding a simple sketch of one, showing that cp is always with shallow water on the left (in the Southern Hemisphere), then three cases of cg (+ve, -ve, and 0 (RF)).

2. Much of the Discussion is actually Introduction (Background) material. Move everything you knew, or should have known, before the study into Introduction. Discussion could keep some implications (regarding sea ice, mixing etc) that depend on the magnitude of the results you have presented, but expectations should be set in Introduction.

3. The discussion of Figure 5 is not very clear. I think the argument you are trying to make is that the "diurnal band" as a whole shows mainly semi-annual, which you ascribe to K1/P1 modulation. Then, K1 (removing P1 influence by inference) is "annual". But the modulation of the diurnal band at the semi-annual frequency is too large for K1+P1, even without the other tidal lines (e.g., O1) being caught in the definition of "diurnal band". Some more thought about this, and an improved discussion, would be useful. It is not impossible that currents and stratification add to a semi-annual term in CTW properties.

4) What does it mean to have a wave whose wavelength *1300 km) is an order on magnitude longer than typical along-slope scales of isobaths variability?

-- Laurie Padman

`Abstract`

`The summer enhancement of diurnal tidal currents at the shelf break in the southern Weddell Sea is studied using velocity measurements from 29 moorings during the period 1968 to 2014. Kinetic energy associated with`

diurnal tidal frequencies is largest at the shelf break and decreases rapidly with distance, and its magnitude increases from austral winter to summer by, on average, 50\,\%. The summer enhancement is observed in all deployments.

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The observations are compared to results from an idealised numerical solution of the properties of coastal trapped waves (CTWs) for a given bathymetry, stratification and an along-slope current. The frequency at which the dispersion curve for mode 1 CTWs displays a maximum (i.e.\ where the group velocity is zero and resonance is possible) is found within or near the diurnal frequency band, and it is sensitive to the stratification in the upper part of the water column and to the background current. The maximum of the dispersion curve is shifted towards higher frequencies, above the diurnal band, for low stratification and a strong background current (i.e.\ winter-like conditions) and towards lower frequencies for strong upper layer stratification and a weak background current (summer).

The seasonal evolution of hydrography and currents in the region is inferred from available mooring data and conductivity-temperature-depth profiles.

Near-resonance between CTWs and the diurnal tides during austral summer can explain the observed seasonality in tidal currents.

Commented [LP1]: The tide-forced CTW’s *are* tides; so maybe better here to say “Near-resonance of diurnal tidal CTWs during …”

\introduction %% \introduction[modified heading if necessary]

Commented [LP2]: I think the Introduction needs to include Nicholls et al., 2009 Reviews of Geophysics.

Also, a lot of Discussion should really be moved to Introduction. Anything relevant that you knew or should have known before starting the study should be in the Introduction.

The shelf break region in the southern Weddell Sea (Fig.~\ref{fig:map}) is an area of great climatic interest. This is where cold, dense Ice Shelf Water emerging from underneath the Filchner-Ronne Ice Shelf (FRIS) descends the continental slope \citep{Foldvik2004}, ultimately contributing to the formation of Antarctic Bottom Water which spreads out into the major oceans at abyssal depths \citep{Orsi1999}. Furthermore, warm off-shelf water crosses the shelf break during summer \citep{Arthun2012} and flows southward towards the Filchner Ice Shelf along the eastern flank of the Filchner Depression \citep[][see map in Fig.~\ref{fig:map} for location]{Foldvik1985d}. The wind driven inflow of Modified Warm Deep Water (MWDW) has been observed to reach the ice shelf front \citep{Darelius2016}, and climate models suggest a larger inflow and a dramatic increase in basal melt rates below the FRIS within the next century \citep{Hellmer2012}.

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Physical processes at the shelf break and on the continental slope influence both the cold outflow and the warm inflow, and to some extent set their hydrographic properties and strengths. The variable depth of the thermocline, for example, which is controlled mainly by wind forcing and eddy overturning \citep{Sverdrup1953, Nost2011} will determine if and when warm water can access the continental shelf \citep{Arthun2012}. Meanwhile, it affects the density contrast between the cold outflow and the ambient water at the shelf break, and thus the strength of the geostrophically balanced outflow \citep{Kida2011, Wang2012} as well as the properties of the descending dense plume since it is a mixture of

Commented [LP4]: Strange sentence. What about the inflow and outflow are "influenced", vs "to some extent set" ? And how do these two things even differ?

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outflow water and ambient water, \citep{Darelius14_Makinson}. The co-location of the critical latitude for the tidal component M2 and a critical slope leads to enhanced turbulence levels in the region \citep{Fer2016}. Mixing can be expected to be further enhanced at the shelf break by the strong diurnal tidal currents and the presence of continental shelf waves \citep{Middleton1987, Foldvik1990, Jensen2013}, a class of coastal trapped waves (CTWs).
This study focusses on tidally generated CTWs at diurnal frequencies in the shelf-break region of the southern Weddell Sea.

Commented [LP5]: Note sure I got the TeX right, but just include Darelius as a regular cite.

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Commented [LP6]: You need to explain the source of the mixing better here. I think you are referring to bottom stress. If you want to claim a baroclinic source of mixing, then needs a cite. Fer et al. paper in prep. would be good, but maybe Ilker's Yermak Plateau paper?

CTWs can be generated by e.g.\ tides \citep{Thomson1982} or wind \citep{Huthnance1995}.
Additionally, a connection between the generation of the waves and the outflow of dense shelf water through troughs has been suggested \citep{Marques2014, Jensen2013}.
CTWs with sub-inertial frequencies propagate along a trapping boundary, e.g.\ a coastal wall or a sloping bottom \citep{Huthnance1995, Huthnance1986}. The waves require the support of such a boundary to exist and decay exponentially with increasing distance from it \citep{Mysak1980}.
While CTWs propagate with shallow water to the left (in the southern hemisphere), the group velocity c_g, and thus the energy associated with the waves, can propagate in either direction.
If the group velocity is zero, i.e.\ for a maximum in the dispersion curve of a wave, energy cannot propagate. When the frequency of this maximum (hereafter called ``resonant frequency'', RF) in the dispersion

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Commented [LP7]: I think this discussion will not make much sense to most readers until you show a dispersion curve for a CTW, even if it is just a schematic showing cp (always shallow water on left), and the three cases of cg>0, cg<0, and RF.

relation coincides with the frequency of tidal currents, resonance may occur and tidal currents will be amplified.

%%%%%%%%%%%%%%

%after editor comment

In practice, it is likely that some energy can escape on one side along the shelf, resulting in near-resonance rather than resonance.

Commented [LP8]: This expression isn't clear; probably need a little introduction to bathymetric irregularity, convergence etc.

%%%%%%%%%%%%%%

Such near-resonant diurnal CTWs were first recorded on the shelf of the Outer Hebrides of Scotland by \cite{Cartwright1969} and have been observed and modelled at numerous occasions and locations since then \citep[e.g.\ ][]{Huthnance1974, Crawford1982, Heath1983, Hunkins1986, Padman1992, Skardhamar2015}.
In our study region, \cite{Foldvik1974} and
\cite{Foldvik85_bottom_currents} first
suggested that CTWs caused the observed strong diurnal tidal currents, which broke down during winter presumably due to a seasonally varying stratification.
Later, \cite{Middleton1987} and \cite{Foldvik1990} found a particularly strong enhancement of the K$_1$ tidal constituent during austral summer.
The summer maximum was hypothesised to be due to the interaction of barotropic CTWs with topography in the presence of a seasonally variable mean current \citep{Foldvik1990}.
These studies were based on a small number of moorings and a barotropic shelf wave model neglecting the effects of stratification.

Our study is based on a more extensive data set and aims to provide new insight into the seasonal variability of the tidal currents at diurnal frequencies and its causes in the southern Weddell Sea.

Observations of current velocities from 29 moorings are used to quantify the strength of diurnal tidal currents and to describe their spatial and temporal variability.

We provide a novel description of the seasonal changes in shelf break hydrography based on observations and use a numerical code \citep{Brink2006} in order to investigate the sensitivity of the CTW properties to seasonal changes in hydrography.

The effects of the stratification and slope current on CTWs are compared, and the influences of the bathymetry and sea ice on CTWs are discussed.

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\section{Data and methods}
\label{sec:methods}
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%mooring data

Current meter data from 29 moorings \citep{Foldvik2004,Jensen2013,Darelius2016} located on the continental slope and shelf in the area surrounding the Filchner Depression have been analysed. The records span the years 1968 to 2013 with each being of 1--2 years duration. The locations of the moorings are shown in Fig.~\ref{fig:map}, and deployment details are listed in Table~\ref{tab:moorings}.

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%coord. system rotation

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The coordinate system is rotated clockwise to align the $y$-axis with the
isobaths, agreeing with the set-up of the numerical code
\citep{Brink2006} in the southern hemisphere. $u$ is thus directed on-
shelf and $v$ along the continental slope (Fig.~\ref{fig:map}). The
rotation angle $\beta$, positive for clockwise rotation, is listed in
Table~\ref{tab:moorings}; it is inferred for each mooring from the local
bathymetry based on the GEBCO\_2014 bathymetry grid (The GEBCO\_2014
Grid, version 20150318, \url{http://www.gebco.net}) with an estimated
accuracy of approximately $\pm$10$^\circ$.

%spectral analysis
Time series of kinetic energy (KE) associated with the diurnal tidal
currents are constructed as follows: The hourly-averaged current meter
data are divided into overlapping chunks of 1.5\,months length beginning
every 14th day. For each chunk, the power spectral densities are
estimated using Welch's method \citep{Welch1976} and three 50\,\%-
overlapping Hanning windows.
%KE
The diurnal tidal KE is obtained by integrating the velocity spectra,
\begin{equation}
\text{KE} = \int^{\omega_{2}}_{\omega_{1}}(S_{u}+S_{v})\,d\omega,
\end{equation}
%where %$u'=u-\bar{u}$ and $v'=v-\bar{v}$ denote the velocity
fluctuations, the overbar indicates time averaging, and
%$S_{u}$ and $S_{v}$ are the power spectral densities of $u$ and $v$,
respectively.
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Commented [LP9]: This approach is sensible, but relies on choosing a length scale for the calculation of local isobaths orientation.

Commented [LP10]: Better word than “chunk” ? Maybe “intervals” ?

Commented [LP11]: So, how long is each window? I think this needs ¾ of a month to work, but that is a bad window length for tides. Better to use 14 or 29 days (more precisely, the spring/neap for O1/K1) where, following \cite{Jensen2013}, ω_{1} and ω_{2} correspond to periods of 26.9\,h and 21.3\,h respectively.

%The results presented are not sensitive to small changes in w1 and w2 (MAKE SURE THAT THEY ARE NOT!)

%CATS

Diurnal tidal KE has also been inferred using tidal predictions from the Circum-Antarctic Tidal Simulation \citep[CATS,][]{Padman2002} for the respective time and location of every mooring deployment. The tidal predictions are treated in the same way as the observational current velocities.

%T_TIDE

Tidal ellipses have been obtained from the mooring records using harmonic analysis \citep[T_TIDE,][]{Pawlowicz2002}, a Matlab version of the FORTRAN code developed by Foreman (1978).

When evaluating seasonal changes, the harmonic analysis was carried out on 50\,\% overlapping month-long segments of the records. The tidal constituent P$_1$ was then inferred from K$_1$ based on the year-long record, since the month-long segments are too short to separate the two signals.

%OTHER DATA

%deployment CTD and seals

Records of temperature and salinity from mooring M3, located at the 725\,m isobath just to the east of the Filchner Trough sill (Fig.~\ref{fig:map}), are used to describe the seasonal changes in

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"… Simulation version 2008b (CATS2008b) an updated version of the tidal inverse model described by Padman et al. (2002)."

Commented [LP13]: This is probably good, but it seems a little bit strange since the energy in the tide model is known exactly for exact frequencies.

Commented [LP14]: Mike Foreman did the really hard work here!

Commented [LP15]: 1) I guess you don't do much with the semidiurnals, but you'd also need to use inference to separate S2 and K2.

2) Inference on K1/P1 assumes that the relative amplitude and phases are constant throughout the year. Given sensitivity of actual CTW currents to exact frequency, is this valid?

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hydrography at the shelf break and upper continental slope. The mooring records are complemented by a conductivity-temperature-depth (CTD) profile obtained during the deployment cruise in 2009 and by hydrographic measurements obtained in the vicinity of the M3 location (within 10\,km, Fig.~\ref{fig:map}) provided by seals tagged with small CTD sensors \citep[described in][hereafter referred to as "seal data"]{Arthun2012}. The accuracies of the seals' temperature and salinity measurements are stated to be 0.005°\,C and 0.02, respectively \citep{Boehme2009}.

%sea ice and Halley
In addition, we use wind observations from Halley Research Station, located at 75°\,35'\,S, 26°\,39'\,W (Fig.~\ref{fig:map}), from 1957 to 2014 \citep{BAS2013} and satellite derived records of sea ice concentration \citep{Meier2013}, available for the period 1978 to 2014. The sea ice concentration is averaged over the study area (inset in Fig.~\ref{fig:map}).

\section{Observational results}

\subsection{Spatial and temporal variability of tidal currents}

%spectral analysis
The diurnal tidal frequency band shows enhanced variance for both the u- and v-component, especially at the frequencies of the most important diurnal tidal constituents K$_1$ and O$_1$ (Fig.~\ref{fig:psd}).

High energy levels are additionally observed at semi-diurnal frequencies and around 35\,h, as reported by \cite{Jensen2013}.

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%KE

The energy associated with the diurnal tidal currents, the diurnal tidal KE (Sect.~\ref{sec:methods}), shows little variation with depth, except for a boundary layer at the bottom where diurnal tidal KE is slightly decreased compared to the overlying water column (Fig.~\ref{fig:hovmollerEKE}). Depth-averaged diurnal tidal KE is used for further analysis.

Commented [LP17]: Figure 3 caption needs to tell us the water depth for each of M5 and M4.

%KE pie map

Figure~\ref{fig:EKEpiemap} shows the spatial distribution of diurnal tidal KE during austral summer. The magnitude of diurnal tidal KE is highest directly at the shelf break (e.g.\ moorings B2, F1, M3) and decreases rapidly with distance from it.
The tidal currents rotate clockwise on the deeper continental slope and anticlockwise at the shelf break and on the shelf.
The major axes of the tidal ellipses at the K$_1$ frequency are directed across the continental slope for moorings located at the shelf break and on the continental slope in the eastern part of the study area, while tidal currents recorded at moorings on the shelf are close to circular.

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Commented [LP19]: You need to talk about what it looks like *west* of the trough, which is different from east of the trough. Otherwise, it looks like you are hiding something. (Are you?!)

%seasonality, explain K1-P1-interference

Time series of diurnal tidal KE (Fig.~\ref{fig:ttidecurrents}a) show two local maxima; one in austral summer and one in austral winter.

These two peaks per year result from the interference of the diurnal tidal constituents K$_1$ and P$_1$, which are in phase every six months. The austral summer maximum is 30\,\% to 180\,\% higher than the winter maximum. This asymmetry is especially strong in records from moorings on the continental slope and at the shelf break, but it is observed in all deployments of sufficient length.

Commented [LP20]: Something is wrong here! P1 and K1 don't explain this high degree of semiannual variability, especially as the "diurnal band" still contains O1.

For moorings on the continental shelf, the difference between the maxima is sometimes less pronounced (e.g.\ Fr2 in Fig.~\ref{fig:ttidecurrents}a).

Minima of the diurnal tidal KE occur near the equinoxes in spring and autumn, when both the sun and the moon are close to the equator.

%normalised t_tide currents

Time series of the K$_1$ magnitude obtained from harmonic analysis on monthly segments (see Section \ref{sec:methods}) show a seasonal signal with a maximum during austral summer which is apparent at all moorings (Fig.~\ref{fig:ttidecurrents}b) with the exception of F1, located at the 647\,m isobath downstream of the Filchner outflow. F1 shows no increase in magnitude towards the end of the record when approaching austral summer.

For all moorings, the semi-major axes are largest in the across-slope component u.

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\subsection{Seasonal variability of the hydrography and current on the upper slope}

\label{sec:hydrography}

%T&S - moor&seal combined plot

The seasonal variability in the hydrography at the shelf break and on the upper slope is investigated by merging all available observational data (moorings, CTD, seal data) near the location of mooring M3 (Fig.~\ref{fig:sealmoor}a,b).

Commented [LP21]: This is a nice figure. However, is it really a “Hovmoller” diagram as stated in the caption?

https://en.wikipedia.org/wiki/Hovm%C3%B6ller_diagram

%

Cold and fresh Winter Water (WW) is found on top of warm and saline MWDW. MWDW is a mixture of WW and Warm Deep Water (WDW), the Weddell Sea version of the Circumpolar Deep Water which is the major component of the Antarctic Circumpolar Current.

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While the temperature in the upper approximately 400\,m is near the freezing point year-round, the salinity of the surface layer increases from 34.0 in February to 34.4 in October. The cold and fresh surface layer during summer likely results from local sea ice melt.

The thermocline is found at a depth of approximately 400\,m from December to April and deepens by 200\,m to approximately 600\,m during May to August. Seasonal changes in the water column below the pycnocline are negligible.

Commented [LP22]: I disagree: In your Figure 6, if I plotted T and S at the bottom of the plot, I would see a seasonal signal.

%

Generally, the seal data show higher salinities and temperatures at depth compared to the mooring data (also compared to the range of the unfiltered mooring records, not shown), suggesting that the MWDW and the thermocline are found higher up in the water column in 2011 compared to 2009. %Differences in seasonal inflow of MWDW onto the shelf have been discussed by \cite{Arthun2012} and \cite{Darelius2016}.

%density profile plot

The density profiles (Fig.~\ref{fig:sealmoor}c) show a gradual increase in density at the surface from $\sigma_0\approx$27.3\,kg\,m^{-3} to 27.7\,kg\,m^{-3}, indicating a relatively stable stratification in the upper part of the water column during austral summer and a relatively homogeneous, weakly stratified upper layer during austral winter.

%slope current

Long-term observations of the westward flowing Antarctic slope current from this area are rare, and our knowledge of its strength, width and variability in our study region are limited. At 12°\,W, \cite{Fahrbach1992} observed a south-westward flowing current following the continental shelf break with annual mean velocities of 10--20\,cm\,s^{-1} and a maximum velocity (hourly average) of over 60\,cm\,s^{-1}. Although inconclusive, the records suggest a wind-driven seasonal cycle with a magnitude of about 5\,cm\,s^{-1} where maximum currents are observed in late autumn.

At 17°\,W, the core of the slope current is found above the 1000\,m isobath with a surface velocity of 50\,cm\,s^{-1} \citep{Heywood1998}. The current is suggested to weaken towards Halley Bay \citep{Fahrbach1992}. It splits at 27°\,W into two branches, one following the coast southwards and one continuing along the continental slope \citep{Gill1973}.

Mooring records from the region west of the Filchner Depression cover only the lower part of the water column, and the observations are greatly influenced by the Filchner overflow plume \citep{Foldvik2004}, thus giving little information about the slope current. East of the depression, the strongest along-slope currents are observed at mooring M3, relatively close to the shelf break at the 750 m isobath. Here, the monthly mean westward current reaches 17\,cm\,s^{-1} during austral winter with maximum values of 25\,cm\,s^{-1}.
At mooring M4 (located at the 1050\,m isobath, less than 10\,km north of M3), no or very weak westward currents were observed.

\section{Numerical code}

\subsection{Set-up}
%(Dispersion curve made up from 50 frequencies)

%general settings
The numerical code described in \cite{Brink2006} and adapted for the southern hemisphere by \cite{Jensen2013}, is used to calculate the properties of stable, inviscid CTWs for different stratification, bathymetry and mean flow.

The code was set up using 30 vertical levels and 120 horizontal grid points to represent a 2\,D-cross-slope section.
Following \cite{Jensen2013}, we use a closed coastal but open offshore boundary, a free surface and a negligible bottom friction as well as the bathymetry used in that study. The bathymetry represents an average of six across-slope sections in the area of moorings M1 to M5, and it compares well to sections farther west in our study area (not shown).

%stratification in the model
The input stratification vector (squared buoyancy frequency, N^2) is linearly interpolated onto the vertical levels of the code and duplicated for the horizontal cross-shelf section before it is converted to density, hence no across-shelf stratification changes are taken into account. If an along-shore current is specified, the background density field is altered by applying the thermal wind equation. The stratification at each level 'n' is then determined from the density difference between levels n-1 and n+1. ~~respective level of the code.~~

%%%

\subsection{Sensitivity to stratification}

%reference stratification
A reference stratification profile was constructed based on all available CTD data collected in January and February in the eastern part of the study area. Similar profiles were constructed for areas farther to the west. Figure~\ref{fig:refstrat}a shows the obtained density and

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stratification profiles, representative for the shelf break at the M-mooring array in austral summer. A simplified version of the stratification profile (Fig.~\ref{fig:refstrat}b) indicates the parameters changed in the sensitivity test: the strengths of the surface magnitude (SM) and the subsurface magnitude (SSM) around 500\,m depth, the depth of the SSM (SSD) and the constant magnitude at depths below 1200\,m (``deep magnitude'', DM). The values of the applied parameter values are listed in Table~\ref{tab:strattest}.

%refstrat -> dispcurve

The dispersion curves and their group velocities for wave modes 1 to 3 corresponding to the reference stratification (Fig.~\ref{fig:refstrat}a) are presented in Fig.~\ref{fig:dispcurve}. Mode 1 is the only wave mode for which the dispersion curve shows a maximum, i.e.\ where the group velocity becomes zero. These results suggest that CTWs with a wavelength of approximately 1260\,km and a period of approximately 30\,h will be trapped while CTWs with tidal frequencies cannot exist.

For tidal CTWs to exist, the dispersion curve must pass through the tidal band, i.e.\ the RF must lie within (thus giving near-resonance) or above the diurnal tidal frequency band.

Commented [LP24]: If the wavelength is really this long, does it make sense to think of these as ‘waves’ when along-slope topography varies on much smaller scales?

i.e., Discuss implications for wavelength >> topo scales

Commented [LP25]: It’s been so long since you mentioned this, you might need to explain it again.

%top strat value

As the numerical code has a vertical resolution of 160\,m, defining the uppermost N^2 value is not a straightforward task. For the reference stratification profile (Fig.~\ref{fig:refstrat}), the surface N^2 value used in the numerical code is from 20\,m depth. Using the surface profile

Commented [LP26]: So … why not use higher resolution in the Brink model? This is the obvious thing to do. I know there are some stability issues with this code, and maybe that’s the answer. But if this is the reason, you need to discuss it here, or maybe better in Section 4.1.

value or an average of the upper 80\,m shifts the dispersion curves and thus the RF to higher frequencies (Fig.~\ref{fig:dispcurve}).

%

%other ref profiles

For stratification profiles which are representative for areas farther west at the shelf break and constructed similarly to the reference stratification with surface N^2 values of the upper 80\,m average, the dispersion curve and RF are similarly shifted to higher frequencies (Fig.~\ref{fig:dispcurve}).

Keeping in mind the variations along the shelf break and with different approaches on how to choose the uppermost stratification value, the characteristic parameters of the reference profile (SM, SSM, SSD, DM, Fig.~\ref{fig:refstrat}b) are varied in the following to explore the general effects of stratification on the dispersion curve and the RF.

%stratification test

Figure~\ref{fig:strattest} shows the results from the sensitivity test for stratification, where the RF is identified from each dispersion curve obtained from the modified stratification input. An increase of N^2 at the surface (case SM) leads to a decrease in RF, which moves through the diurnal tidal frequency band for the modelled range of surface stratification. In contrast to case SM, an increase of the stratification maximum at approximately 640\,m depth (case SSM) increases the RF.
The effect of an increase in depth of the subsurface maximum (case SSD) results in an apparent decrease of the RF. However, due to the interpolation in the numerical code, the stratification around the

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subsurface maximum as well as the exact value of the maximum are difficult to preserve. Hence, the actual effect of case SSD appears to be rather small.
Varying the stratification below 1200\,m depth (case DM) has a negligible effect on the RF.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%current sensitivity test
\subsection{Sensitivity to along-slope current} %Merge maybe with stratification section

%current parameters
The optional along-shore current has a Gaussian shape; its offshore, onshore, upward and downward $e$-folding length scales must be specified, in addition to the centre position, strength and depth of the current.

For the sensitivity test, a barotropic (i.e.\ with a large vertical length scale) westward current is assumed which is centred at the shelf break.
The density is set to be undisturbed at the coast when the density field is altered according to the thermal wind equation, with the input $N^2$ vector being the reference stratification for all runs.
The width and strength of the current are varied from 10 to 100\,km and 0.1 to 0.5\,m\,s$^{-1}$, respectively (Fig.~\ref{fig:currenttest}).
Generally, both a stronger and a wider current lead to an increase in RF; with the effect of strength being largest.
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Commented [LP27]: Figure 10 needs O1 and K1 frequency lines marked.

Moving the location of the current core 40\,km on (off) shore, the sensitivity of the RF is increased (reduced) slightly compared to a current core at the shelf break. The magnitude of change in RF equals approximately a change in current velocity of $\pm$10\,cm\,s^{-1} (not shown).

Commented [LP28]: I do not like this bracketed way of doing opposite cases. In general, you can ignore the bracketed examples as they are implied as the opposite of the main case. If that isn't true, then you'd need a clear sentence for the opposite case anyway.

Although the overall effect of an added barotropic slope current is minor compared to the sensitivity to changes in stratification (cp.\ y-axes in Fig.~\ref{fig:strattest} and Fig.~\ref{fig:currenttest}), the sensitivity depends noticeably on the vertical length scale. As an example, a 40\,km wide and 0.2\,m\,s^{-1} fast current is chosen and its downward e-folding length scale is reduced from 4300\,m to 2000\,m. The RF is then considerably larger (open circle in Fig.~\ref{fig:currenttest}) than for the more barotropic case.

Commented [LP29]: I think you mean 'cf.', but use "compare the" instead

\section{Discussion}

Commented [LP30]: A lot of the Discussion is actually Introduction/Background, that should have told you what to expect before you got to the end. Almost every sentence with cites could have come earlier. As just one example, discussion of the Skarohamar et al. (2015) *model* result could have been used in the Introduction to point to 3-D model support for the more idealized analyses of, e.g., Middleton et al. 1987.

So, thin out the Discussion and strengthen the Introduction.

Observations from the continental slope in the southern Weddell Sea show anomalously strong tidal currents at diurnal frequencies \citep{Middleton1987}. Our extended analysis - including all current meter records (1968--2014) from the region - confirms previous findings suggesting that the strong currents are the result of tidally forced CTWs \citep{Middleton1987,Foldvik1990,Foldvik85_bottom_currents}. The observations agree qualitatively with the mode 1 CTW "generated" in the numerical code by \cite{Brink2006}, Fig.~\ref{fig:allplot}; notably the

direction of rotation changes at the slope, and the strength of the currents increases towards the shelf break, as expected.
The dispersion relation obtained from the model when using bathymetry and stratification representative for the region (Fig.~\ref{fig:dispcurve}) suggests that diurnal CTWs may be near-resonant, i.e.\ that the group velocity is zero or close to zero so that energy cannot propagate out of the area resulting in amplified diurnal tidal currents. A similar result was obtained by \cite{Middleton1987} using a barotropic shelf wave model \citep{Saint-Guily1976}. Tidal currents may be enhanced for a range of frequencies surrounding the RF, and thus RF does not need to coincide exactly with a tidal frequency for amplification to occur \citep{Chapman1989}.

The dispersion curves in Fig.~\ref{fig:dispcurve} show that while the CTWs are relatively barotropic in the region \citep[according to the Burger number, $Bu= \left(\frac{NH}{fL}\right) ^2$, $Bu\ll1$, where N^2 is stratification, f the Coriolis factor and H and L are representative depth and length scales, respectively;][]{Wang1976,Brink2006,Jensen2013}, the dispersion curve is sensitive to relatively small changes in the stratification.

%%%%%%%%%%%%%%%%%%%

Time series of the KE associated with the diurnal tides and of the tidal amplitudes derived by harmonic analysis show that diurnal tidal currents consistently are enhanced by 30--180\,\% during austral summer.

%%%

Commented [LP31]: 1) How does a dispersion curve show that the CTWs are relatively barotropic? I *think* the answer might be that Mode-1 is the only CTW Mode that can get close to diurnal frequencies, but the modal structure refers to the number of zero crossing across-slope, right? Not the vertical structure.

You then present a Burger number argument, which makes more sense, but is not explicitly related to the CTW dispersion curves. Better to just argue based on Burger number, or extract something from the Brink model that explicitly demonstrates that the mode(s) is(are) barotropic.

%The diurnal tidal forcing does not vary on seasonal scales and thus cannot explain the enhancement.

The astronomical diurnal tidal forcing and its seasonal variability cannot explain the asymmetry of the maxima in diurnal tidal KE.

Commented [LP32]: This is too vague. Be explicit about the magnitude of the "seasonal" variability you would expect from astronomical forcing (basically, what modulation do you expect from the K1/P1 couplet?) and state that it is semi-annual (Figure 5a) not annual (Figure 5b)

%%%

Studying a small subset of the moorings, \cite{Foldvik85_bottom_currents} hypothesised that changing stratification causes the breakdown of the diurnal tidal currents observed during austral winter of 1968, while \cite{Foldvik1990} suggested that the seasonality was linked to the variability of the slope current. Other potential explanations are seasonal changes in the sea ice cover, as high sea ice concentrations would potentially dampen the CTWs \citep{Ono2008}, or in wind forcing, which could potentially excite CTWs \citep{Gordon1987} at diurnal frequencies. These influences will be discussed below.

Commented [LP33]: Mack et al., 2013, GRL, show nicely that sea ice responds to the tides (for the Ross Sea). Padman and Kottmeier, 2000, JGR (already cited) show tidal motion of ice for the Weddell Sea. If ice is mobile, it can't dissipate tidal energy; it is "free drift". It's ice mechanics at high ice concentration that provides the friction needed to reduce tides.

%Time series of the KE associated with the tides and of the tidal amplitudes derived by harmonic analysis show that while the tidal forcing is constant, the tidal currents consistently are enhanced by 30--180\,\% during austral summer. This was noted in a subset of the moorings by \cite{Foldvik1990}, who suggested that the seasonality was linked to the variability of the slope current. In an earlier study, the breakdown of the diurnal tidal currents observed during austral winter of 1968 was hypothesised to result from changing stratification \citep{Foldvik1974}. Other potential explanations are seasonal changes in the sea ice cover, as high sea ice concentrations would potentially dampen the CTWs \citep{Ono2008}, or in wind forcing, that could potentially excite CTWs \citep{Gordon1987} at diurnal frequencies. These influences will be discussed below.

%%%%%%%%%%%%%%%%%%%%

Hydrography and currents, which are known to vary seasonally, will alter the properties of the CTWs \citep[e.g.\ ][]{Marques2014, Jensen2013, Brink1991, Wang1976}. We hypothesise that the observed seasonality in the diurnal tidal currents is indirectly linked to seasonal changes in the oceanographic "background", as it determines the dispersion relation including the RF for the CTWs which are responsible for the tidal amplification in the area.

Commented [LP34]: All Introduction text

The largest seasonal changes in the shelf break hydrography in the region occurs, similar to regions farther east in the Weddell Sea \citep{Nost2011,Graham2013}, above the pycnocline. Cooling and a gradual increase in salinity (due to ice freezing and brine rejection) during austral autumn and winter leads to a gradual deepening of the surface layer. Towards the end of the winter (August--September) the upper 400\,m are relatively homogeneous. During summer, the winter layer is capped by a fresh and relatively warm surface layer which likely is the result of local sea-ice melt and solar heating. The layer of summer surface water is thin (10-100\,m, see CTD-profile in Fig.~\ref{fig:sealmoor}) and greatly increases the stratification by creating a seasonal, shallow pycnocline. The sensitivity test (Fig.~\ref{fig:strattest}) shows that the value of the RF is sensitive to the stratification in the upper layer (SM) and that it increases for decreasing stratification. The response in RF to realistic changes in SM is of sufficient magnitude to cause the RF to move through the diurnal tidal band.

While the RF is influenced by changes in the strength of the permanent (deeper) pycnocline (SSM), which is the manifestation of the transition from WW above to MWDW and WDW below, there is no observational evidence suggesting that it would change in magnitude. The depth of the permanent pycnocline (SSD), however, increases from about 400\,m in summer to about 600\,m, but changes in SSD have little or no influence on the RF.

\cite{Foldvik1990} showed how changes in the background current will affect the phase of diurnal CTWs, which are assumed to be generated upstream, as they arrive in the study region. Here we have investigated, similar to the work by \cite{Skardhamar2015}, the effect of changes in the background current on the dispersion relation and hence on the possibility for local near-resonance.

Commented [LP35]: All Introduction text

The available observations do not allow us to describe either the nature or the variability of the slope current, but the data from mooring M3 suggest that, in agreement with observations upstream \citep{Nost2011,Graham2013,Nunez2009}, the westward flowing slope current is intensified during austral winter. When a barotropic, westward background current is included in our set-up, the dispersion curve (and thus the RF) is shifted toward higher frequencies \citep[Fig.~\ref{fig:currenttest} and][]{Jensen2013}, but the effect is small compared to the effect of stratification changes. The stronger current observed during austral autumn and winter will however add to the effect of the low winter time stratification and move the RF upwards.

While the tidal force is the main generation mechanism for CTWs in the diurnal tidal band \citep{Thomson1982}, CTWs can also be generated by winds \citep{Huthnance1986}. Short duration storms have been observed to excite near-resonant CTWs of mode 1 \citep{Gordon1987}, i.e.\ the response to storms would in our case resemble the tidally forced waves. Time series of wind from the nearby Halley Research Station (see Fig.~\ref{fig:map} for location), however, show that storms (wind speed $>$20\,m\,s^{-1}) are rare during austral summer and, as expected, more frequent during winter and early spring. CTWs induced by storms can hence not explain the summer enhancement of the diurnal tidal currents. Fourier analysis of the time series reveals a daily cycle in wind strength with an increase of magnitude of up to 1.4\,m\,s^{-1} around noon, which likely results from local boundary layer effects: The stable boundary layer which develops during the night is destroyed during the day by mixing due to solar insolation \citep[see, e.g.\ ][]{Stull2012}. Since the signal is weak, we conclude that these oscillations are not responsible for the observed summer amplification.

The study region is fully or partly covered by sea ice throughout the year, with the coverage normally exceeding 90\,\% during winter (mid-April to mid-November) and decreasing to a minimum of on average 50\,\% in February with considerable spatial differences within the study region (Fig.~\ref{fig:seaice}). Frictional damping of tidal CTWs due to sea ice is suggested to be the cause of the observed reduction of tidal currents over the shelf in the Sea of Okhotsk \citep{Ono2008}. The damping is observed only at the mooring farthest away from the generation site of the waves, indicating an increasing effect of the damping with distance.

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The authors do not explain why the period with reduced tides are much
shorter (and misaligned) compared to the period with dense ($>$80\,\%)
sea ice cover. While we can neither quantify nor rule out the effect of
sea ice concentration, we note that the semi-diurnal tidal currents are
observed to be larger during austral winter than during summer
\citep{Foldvik1990}, thus questioning a general damping effect.

\cite{Skardhamar2015} studied diurnal tides on the Barents Sea
continental slope in a 3\,D-model and concluded that the tidally
generated CTWs were confined to a region with diverging bathymetry. Just
east of our study region, the continental slope is much steeper
(Fig.~\ref{fig:map}), that is, the isobaths diverge towards the west. The
dispersion curve obtained using the steeper, eastward bathymetry is
shifted upward with respect to the gentler slope in the study region
(Fig.~\ref{fig:dispcurve}).
%%%
Tidal energy travelling westward along the steep, eastern part of the
slope could potentially be "piling up" in the more gently sloping study
region where westward propagation no longer is possible.
%%%
Above the steep, eastern slope, there are no direct observations of tidal
currents, but the tidal motion of sea ice above the shelf break there
suggests much weaker currents \citep{Padman2000}. A full 3\,D-analysis,
similar to the one by \cite{Skardhamar2015}, would be needed to fully
explore the effect of bathymetry.
%Although there are no direct observations of tidal currents above the
steep, eastern slope, the tidal motion of sea ice above the shelf break
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Commented [LP36]: Most of this is Introduction text there suggests much weaker currents \citep{Padman2000}. A full 3\,D-analysis, similar to the one by \cite{Skardhamar2015}, would be needed to fully explore the effect of bathymetry.

The anomalously large diurnal tidal currents and the CTWs will influence e.g.\ the ice cover \citep{Padman2002}, and, potentially, the exchange of WDW across the shelf break. In an idealised model study, CTWs were shown to enhance the inflow of warm water through a trough cross-cutting the continental shelf \citep{Stlaurent2013}, similar to the Filchner Depression. We note that the depth of the WW--WDW transition (identified e.g.\ by the -1°\,C isotherm) varies on diurnal time scales (Fig.~\ref{fig:pycnovary}a), and e.g.\ in December 2009, the vertical excursion of the isotherm associated with the diurnal tides is $>$100\,m (Fig.~\ref{fig:pycnovary}b). The depth of the transition is likewise affected by CTWs with 35\,h period \citep[Fig.~\ref{fig:pycnovary}a,][]{Jensen2013}. The existence and strength of diurnal \citep[and longer period,][]{Jensen2013} CTWs in the region must hence be expected to directly influence the availability of warm water above the shelf depth, i.e.\ at depths where it can potentially access the continental shelf. Furthermore, it was recently shown that elevated turbulence levels in the shelf-break region are linked to the semi-diurnal tide and the co-location of critical slope and critical latitude \citep{Fer2016}. The tides thus influence the water mass properties (through mixing) as well as the strength and depth of the thermocline at the shelf break. Modelling efforts aiming to describe and predict the oceanic heat transport towards the FRIS cavity inflow thus

Commented [LP37]: Not the right cite. Various available, including Kowalik and Proshutinsky 1994, Padman and Kottmeier, 2000; Mack et al., 2013.

Commented [LP38]: I’m not sure why this figure only comes up in Discussion: seems like “Results” to me.

Commented [LP39]: Raising warm water above the shelf-break depth does not, by itself, do anything. *Ignoring friction*, CTWs just conserve vorticity; “the tide goes up, the tide goes down”.

So, the key to this being important lies in coupling, either with mean flows or friction. Or, as some people have studied, the rectified flows that arise from tidal interactions over sloping topography.

Your paper is not about these processes, and doesn’t need to be, but this section needs a little more information to avoid being misleading.

ought to include tidal forcing to correctly capture the dynamics at the shelf break.

Finally, we mention that the observed diurnal tidal currents are up to one order of magnitude larger than those predicted by the tidal model CATS2008 \citep[Fig.~\ref{fig:allplot},][]{Padman2002}, and that the predictions from CATS do not reveal the summer enhancement.
Moreover, due to errors in the model bathymetry, the predicted peak tidal currents are not consistently aligned with the shelf break when running CATS along a cross-shelf section through the locations of moorings M1 and M2 (see Fig.~\ref{fig:allplot} and Fig.~\ref{fig:map} for location of section).
Hence, care must be taken when using CATS to de-tide velocity observations from the region.

Commented [LP40]: Yes? Even if not, specify exactly which one.

Commented [LP41]: This is a bit unfair: CATS, like every other tide model, is a barotropic model with only tides included.

More honest to say

"… CATS2008 (Figure 11), which does not include stratification or the variability of mean circulation required to predict seasonal modulation of tidal current."

%%%

\conclusions%[alternative title]

Velocity measurements at 29 moorings located on the continental slope and shelf in the southern Weddell Sea from the period 1968 to 2014 show pronounced diurnal tidal variability. Diurnal tidal currents are strongest at the shelf break and substantially enhanced during austral summer. The summer enhancement is not predicted by the tidal model CATS2008 \citep{Padman2002}.
We investigated the possibility for near-resonant CTWs causing the enhanced diurnal tidal currents by using a 2\,D-numerical code to obtain

Commented [LP42]: Repeating preceding comment:

This is a bit unfair: CATS, like every other tide model, is a barotropic model with only tides included.

More honest to say

"… CATS2008 (Figure 11), which does not include stratification or the variability of mean circulation required to predict seasonal modulation of tidal current."

CTW properties \citep{Brink2006}. Dispersion curves of mode 1 CTWs have a maximum in frequency (the resonant frequency, or “RF”), which results in zero group velocity, i.e.\ trapped energy. The RF moves in and out of the diurnal tidal frequency band depending on the stratification and the slope current which both vary seasonally as hydrographic and current observations at the shelf break reveal. For the weakly stratified water column and strong slope current during austral winter, the RF is found above the diurnal band, suggesting the generation of weak, non-resonant tidal CTWs which quickly propagate out of the generation area. For austral summer conditions, i.e.\ a more stratified upper water column combined with a weaker slope current, the RF can fall into the diurnal band, thus leading to near-resonant diurnal CTWs enhancing the tidal currents.

Commented [LP43]: In Conclusions, minimize acronyms even if explained earlier. If useful here, explain them again.

Deleted:

While no direct influence of wind on the diurnal tidal currents has been found, the varying bathymetry east of the study area as well as the sea ice cover likely affect the propagation of the CTWs. Further studies, using 3\,D-models for example, are needed to quantify these influences as well as to detect the generation site of the CTWs.

Commented [LP44]: Huh?! How can you say “likely” when you have no direct evidence of something? Maybe the problem here is mixing the diurnal wind forcing issue with the others. I think your conclusions are:

“No evidence for wind forcing of diurnal tidal currents.”

“No evidence that sea ice affects the diurnal CTWs.”

“Varying bathymetry east of the study area likely affects the CTWs seen in the study area.”

However, varying bathymetry anywhere affects the CTWs, so why only comment here on the upstream?

The shelf break region in the southern Weddell Sea is an area of great climatic interest. Cold, dense Ice Shelf Water descends the continental slope and contributes eventually to the formation of Antarctic Bottom Water, while warm MWDW flowing onto the shelf prospectively may reach the cavity below FRIS, thus enhancing basal melt rates. The strong diurnal tidal currents at the shelf break facilitate the cross-shelf exchange of water masses and contribute to mixing, hence influencing the hydrographic properties of both the cold outflow and warm inflow.

%The shelf break area in the southern Weddell Sea is a region of high climatic interest - cold, dense ISW from the FRIS cavity descends the continental slope and contribute to bottom water formation \citep{Foldvik2004} and future scenarios suggest that the inflow of WDW towards the cavity will greatly enhance FRIS basal melt rates in the near future \citep{Hellmer2012}. The strong tidal currents will influence the cross shelf break transport and the hydrographic properties (through mixing) of both the cold outflow and the warm inflow.
% oNE LAST SENTENCE ON THE NEED FOR A 3-d MODEL A LA sKARDHAMAR?

%\appendix
%\section{}   %% Appendix A
%\subsection{} %% Appendix A1, A2, etc.

\begin{acknowledgements}
For deployment and recovery of moorings, we would like to thank AWI and the crew and scientists on RV \textit{Polarstern} cruises PS08 (recovery of moorings D1, D2, S2-1985 and S3), PS12 (deployment S2-1987), PS34 (deployment Fr1 and Fr2), PS53 (recovery F1--4) and PS82 (recovery SB, SC, SD and SE).
We would also like to thank K. Brink for sharing the numerical code and I. Fer for helpful comments and suggestions.
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\end{acknowledgements}