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Wfind finffluence on resfiduafl cfircuflatfion fin Patagonfian channefls and fjords

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ABSTRACT

Cfircuflatfion fin estuarfies fis typficaflfly consfidered to be drfiven by horfizontafl densfity gradfients, caflfled gravfitatfionafl cfircuflatfion, but can be modfiffied by other forcfing such as the wfind. Studfies have shown that wfind finffluence can efither augment or counteract densfity-drfiven resfiduafl fflows fin estuarfies, but the temporafl and spatfiafl extent of thfis finffluence remafins unknown, partficuflarfly fin deep and hfighfly stratfiffied fjords. Thfis study afims to fffflthfis gap by finvestfigatfing the seasonafl varfiabfiflfity fin resfiduafl cfircuflatfion, wfind forcfing, and stratfifficatfion fin an extensfive fjord and channefl system fin Chfiflean Patagonfia. Observatfions of current veflocfity and wfind are suppflemented by atmospherfic and hydrodynamfic cfircuflatfion modefls fin the Morafleda Channefl, a system that connects the fjord system of Northern Patagonfia to the Pacfiffic Ocean. Resuflts show a marked seasonaflfity, gfiven that the surface outfflow fis reversed by wfind forcfing durfing the wfinter, a season characterfized by strong southward (up-channefl) wfinds. Thfis produces a near-surface fflow dfirected up-channefl fin the upper ~40 m of the water coflumn, fin opposfitfion to the horfizontafl pressure gradfient. Cross-channefl transects reveafled that the vertficafl structure of the aflong-channefl resfiduafl veflocfity was three-flayer durfing the wfinter. The near-surface (<50 m) aflong-channefl current on the eastern sfide of the channefl foflflowed the wfind dfirectfion (southward). Between 50 and 100 m depth the fflow was out-channefl and beflow 100 m depth the fflow was agafin fin-channefl. On the western sfide, the aflong-channefl resfiduafl fflow was two-flayer, wfith near surface fflow dfirected northward (agafinst the wfind) wfith a return fflow beflow (deeper than 50 m). Durfing the sprfing, northward (out-channefl) wfinds domfinated and the vertficafl structure of the aflong-channefl resfiduafl veflocfity was two-flayer, augmentfing the horfizontafl pressure gradfient, whfich stabfiflfized the water coflumn, enhancfing stratfifficatfion, finhfibfitfing mfixfing and eflevated gravfitatfionafl cfircuflatfion.

1. Introduction

The gravfitatfionafl cfircuflatfion, forced by horfizontafl densfity gradfients, fis known to be a prfimary drfiver of resfiduafl fflows fin estuarfies (Geyer and MacCready, 2014; Lange et afl., 2020), whereas the rofle of the wfind has recefived reflatfivefly fless attentfion fin contrast to studfies on tfidafl and densfity forcfing. Severafl studfies have focused on understandfing and characterfizfing the estuarfine cfircuflatfion fin fjords (Stfigebrandt, 1981; Geyer and Cannon, 1982; Sfiflva et afl., 1995; Caceres et afl., 2002a; Sutherfland et afl., 2014; Castfiflflo et afl., 2012; Castfiflflo et afl., 2016; Wan et afl., 2017; Shan et afl., 2019). The ffirst conceptuafl cfircuflatfion modefls of Patagonfian Fjords prepared by Sfiflva et afl. (1995) descrfibed freshwater fflow to the ocean at the surface and saflty ocean water at depth fflowfing to the finterfior of the channefls; a resuflt anaflogous to the cflassficafl two-flayer estuarfine cfircuflatfion of Prfitchard (1954) drfiven by horfizontafl densfity gradfients. On the other hand, studfies that are more recent, have reveafled the finffluence of tfides fin aflterfing thfis typficafl estuarfine cfircuflatfion structure (Geyer and Farmer, 1989; Ifi and Ifi, 2011; Geyer and MacCready, 2014; Vaflfle-Levfinson et afl., 2014; Gfiddfings and MacCready, 2017; Ross et afl., 2017).

In a study by Vaflfle-Levfinson et afl. (2014), they proposed that the cfircuflatfion structure fin fjords that experfience tfidafl forcfing can have three vertficafl flayers, specfifficaflfly fin deep fjords where the water coflumn depth fis sfix tfimes deeper than the bottom boundary flayer. There are three types of water masses found fin the fjords and channefls of Patagonfia (Sfiflva et afl., 1998). The ffirst corresponds to the Estuarfine Water (EW) surface flayer between 0 m and ~25 m depth. The mfiddfle flayer corresponds to Sub-Antarctfic Water and Modfiffied Sub-Antarctfic Water (SAAW and MSAAW), between 30 m and 150 m, and the thfird, Equatorfiafl Subsurface Water (ESSW), occurs from 150 m to the bottom. Usfing observatfionafl current data, studfies have found a three-flayer vertficafl structure of aflong-channefl resfiduafl fflows and have suggested that

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finffluence from the wfind (Cáceres et afl., 2002a) or tfides (Vaflfle-Levfinson et afl., 2007) can aflter the three-flayer structure.

Wfind contrfibutfion to the estuarfine cfircuflatfion, characterfized fin a semfi-cflosed basfin by vertficafl downwfind surface fflows and up wfind return fflows underneath (Wong and Lu, 1994; Vaflfle-Levfinson et afl., 2002; Wan et afl., 2022), has not recefived much attentfion fin fjords. Studfies have shown that wfind-finduced fflows can predomfinate fin estuarfies wfith weak tfidafl finffluence (Prfitchard and Vfiefira, 1984; Geyer, 1997). Geyer (1997) pofinted out that wfind-finduced forcfing can domfinate gravfitatfionafl cfircuflatfion fin shaflflow estuarfine systems, and thfis fin turn controfls the saflfinfity structure and resfidence tfime. More recent studfies on estuarfine systems fin the Northern Hemfisphere (Scuflfly et afl., 2005; Lfi and Lfi, 2011; Xfie and Lfi, 2018) have suggested that the dfirectfion of the wfind wfffl determfine fits rofle fin mfixfing or stabfiflfizfing the estuary waters.

Wfind drfiven currents are typficaflfly known to enhance mfixfing and shear fin the surface flayer, whfich can break down stratfifficatfion and deepen the pycnocflfine (Lfi et afl., 2007; Ross et afl., 2015; Perez-Santos et afl., 2019). However, Scuflfly et afl. (2005) found that down-estuary wfind can augment the surface flayer of the resfiduafl fflow, enhancfing stratfifficatfion aflong the channefl, and termed thfis mechanfism "wfind-strafinfing". Wfindstrafinfing has been found to be an fimportant drfiver of the estuarfine cfircuflatfion (Wefisberg and Sturges, 1976; Geyer, 1997; Scuflfly et afl., 2005; Chen et afl., 2009; Lange and Burchard, 2019). However, the wfind may not act homogeneousfly fin an estuary. Thus, dfifferent regfions fin the estuary must be taken finto consfideratfion when the wfind-current response fis finvestfigated (Xfie and Lfi, 2018). In fjords, the mountafinous terrafin can funnefl wfind fin the axfiafl dfirectfion, whfich coufld efither augment or counteract the gravfitatfionafl cfircuflatfion (Inaflfl and Gfiflflfibrand, 2010), but the effects flargefly remafin unknown.

Understandfing the finffluence of wfind on the estuarfine cfircuflatfion fis fimportant as fit can finffluence the current structure, current veflocfity, stratfifficatfion/mfixfing, exchange fflux, resfidence tfime and transport. Cfircuflatfion strength and structure fimpacts the abundance of nutrfients, whfich among other forcfing factors, has fled to recurrfing Harmfufl Aflgafl Bflooms (HABs) fin Patagonfian Fjords and Channefls (Muñoz et afl., 1992; Guzmán et afl., 2002; Mardones et afl., 2010, 2021; Pfizarro et afl., 2018; Díaz et afl., 2021; Crawford et afl., 2021). Saflmon and mytfiflfidae (mussefl) farmfing fis proflfiffic fin thfis regfion, and therefore the effects of HABs have had dfisastrous consequences for thfis findustry.

HABs have affected the Chfiflean saflmon findustry by causfing massfive mortaflfitfies, yet there fis controversy over whether the contrfibutfion of excess nutrfients from saflmon farms exacerbates the aflgafl bflooms (Qufiñones et afl., 2019). Estuary resfidence tfimes dfictate how flong eflevated nutrfient flevefls and HABs wfffl remafin fin a partficuflar system (Lucas, 2010), and the resfidence tfimes can be dependent on the estuarfine cfircuflatfion (Pfinfiflfla et afl., 2020). Resfidence tfimes can aflso fimpact bfiogeochemficafl and bfioflogficafl processes (Gfiddfings and MacCready, 2017) such as phytopflankton (Davfis et afl., 2014) and poflflutant (Gfiddfings and MacCready, 2017) transport, and the deveflopment of hypoxfic condfitfions (Perez-Santos et afl., 2018). Therefore, to fidentfify the causes of eutrophficatfion and fits fimpflficatfions on Patagonfian fjord ecosystems, such as HABs, we must ffirst form a better understandfing of the spatfiafl and temporafl structure of fjord stratfifficatfion, mfixfing, and cfircuflatfion.

The afim of thfis research fis to eflucfidate the competfitfion between the fflow finduced by freshwater and that forced by the wfind. Thfis goafl wfffl be accompflfished by finvestfigatfing fjord cfircuflatfion structure and how spatfiafl and temporafl varfiatfions fin the structure are flfinked to spatfiafl varfiatfions fin stratfifficatfion and mfixfing durfing seasons wfith contrastfing wfind dfirectfions and magnfitudes. The study wfffl be conducted fin a Patagonfian Fjord and Channefl system fin Chfifle, the Morafleda Channefl, and wfffl fincflude anaflysfis of *fin-sfitu* coflflected data and a three-dfimensfionafl coupfled atmosphere-ocean hydrodynamfic modefl.

2. Materials and methods

2.1. Study area

The Morafleda Channefl (Ffig. 1) connects the coastafl ocean (Boca defl Guafo and flaterafl channefls) wfith the finfland sea (fjords: Jacaf, Puyuhuapfi, Aysen, Qufitraflco, Cupqueflan) fin Northern Patagonfia. The channefl has a north-south orfientatfion wfith a flength over 160 km and a wfidth between approxfimatefly 12 km and 25 km. It fis dfivfided finto two basfins: the northern basfin wfith depths exceedfing 300 m, and the shaflflower southern basfin wfith depths as shaflflow as 40 m fin the Menfinea constrfictfion-sfiflfl, whfich has been known to restrfict exchange fflows (Sfiflva et afl., 1995; Vaflfle-Levfinson et afl., 2002).

The recorded average monthfly precfipfitatfion (from the Boca defl Guafo to Aysen Fjord) fis hfighest fin the Austrafl wfinter months >200 mm, compared wfith the Austrafl summer, when fit fis < 200 mm (Caflvete and Sobarzo, 2011). The mafin source of freshwater comes from rfivers and gflacfiers, of whfich the prfimary finputs fincflude: the Paflena Rfiver, Cfisnes Rfiver, Aysen Rfiver, and the gflacfiafl meflt from the Northern Iceffiefld. There are two dfischarge maxfimums per year (Tabfle 1), wfith one fin the wfinter (due to rafinfaflfl) and one fin the sprfing (due to fice meflt). These dfischarge scenarfios create a brackfish water gradfient from the fjords to Boca defl Guafo, gfivfing rfise to an estuarfine cfircuflatfion domfinated by outfflow of flow saflfinfity water over finfflow wfith hfigh saflfinfity (Sfiflva et afl., 1995, 1997, 1998; Caflvete and Sobarzo, 2011). In a study wfith a hydrodynamfic modefl, Rufiz et afl. (2021) categorfize the Morafleda Channefl as a hfighfly stratfiffied system fin the summer and weflfl-mfixed fin the wfinter.

Tfides fin Morafleda Channefl are mfixed wfith semfidfiurnafl domfinance wfith maxfimum sprfing tfide ampflfitudes of 2.8 m. Durfing neap tfides thfis ampflfitude decreases by approxfimatefly one haflf (Pfierro et afl., 2000; Vaflfle-Levfinson et afl., 2002). The semfidfiurnafl tfidafl propagatfion occurs through the Chonos Archfipeflago rather than aflong Morafleda Channefl due to the flarge phase flag sustafined across the Boca defl Guafo (Afiken, 2008).

The regfionafl wfind varfiabfiflfity fis finffluenced by the westerflfies and the Southeast Pacfiffic Subtropficafl Antficycflone (SPSA). In Chfiflean Patagonfia, these atmospherfic forcfings dfispflay partficuflar characterfistfics. The westerflfies are stronger than fin the Northern Hemfisphere and the SPSA presents a mfigratfion to the south fin the austrafl summer, whfich expflafins the seasonafl wfind regfime (Stewart, 2002; Perez-Santos et afl., 2019). Thfis has been recorded at Guafo fisfland, wfith predomfinant southerfly and southwesterfly wfind durfing the austrafl sprfing-summer and northerfly and northeasterfly wfinds durfing the faflfl-wfinter season (Cáceres et afl., 2002a; Vaflfle-Levfinson and Bflanco, 2004; Narváez et afl., 2019). The hfighest wfind veflocfitfies can reach magnfitudes over 10 m/s (Vaflfle-Levfinson et afl., 2002), whfich domfinate fin wfinter and sporadficaflfly occur fin sprfing/-summer (Cáceres et afl., 2002a; Vaflfle-Levfinson and Bflanco, 2004).

2.2. In-sfitu measurements

Current veflocfity measurements were coflflected usfing a 307.2 kHz RD Instruments Acoustfic Doppfler Current Proffifler (ADCP). The flocatfion of the depfloyment was fin Morafleda channefl where the depth fis 368 m (Ffig. 1). The depfloyment flasted from wfinter of 2018 (August 8th) to summer of 2019 (March 10th). The finstrument was moored at 67 m depth wfith the transducers facfing up and coflflected data every 30 mfin (50 pfings per ensembfle) wfith a vertficafl bfin resoflutfion of 4 m. The ffirst bfin was flocated 6.1 m from the ADCP. Data fin the upper 9% of the coflumn were removed to eflfimfinate sfide flobe effects, aflflowfing for measurements coflflected from approxfimatefly 5 m–61 m depth.

An autospectrafl anaflysfis (e.g., Saflfinas and Castfiflflo, 2012) was appflfied to the ADCP data to determfine the domfinant frequencfies of varfiabfiflfity fin the current veflocfitfies (Bendat and Pfiersofl, 1986). The tfime serfies was wfindowed and resuflted fin 14 degrees of freedom (Emery and Thomson, 1998). The energy densfity spectrum was then fintegrated finto dfiurnafl (10–14 h), semfi-dfiurnafl (22–26 h) and flow-frequency (3–15

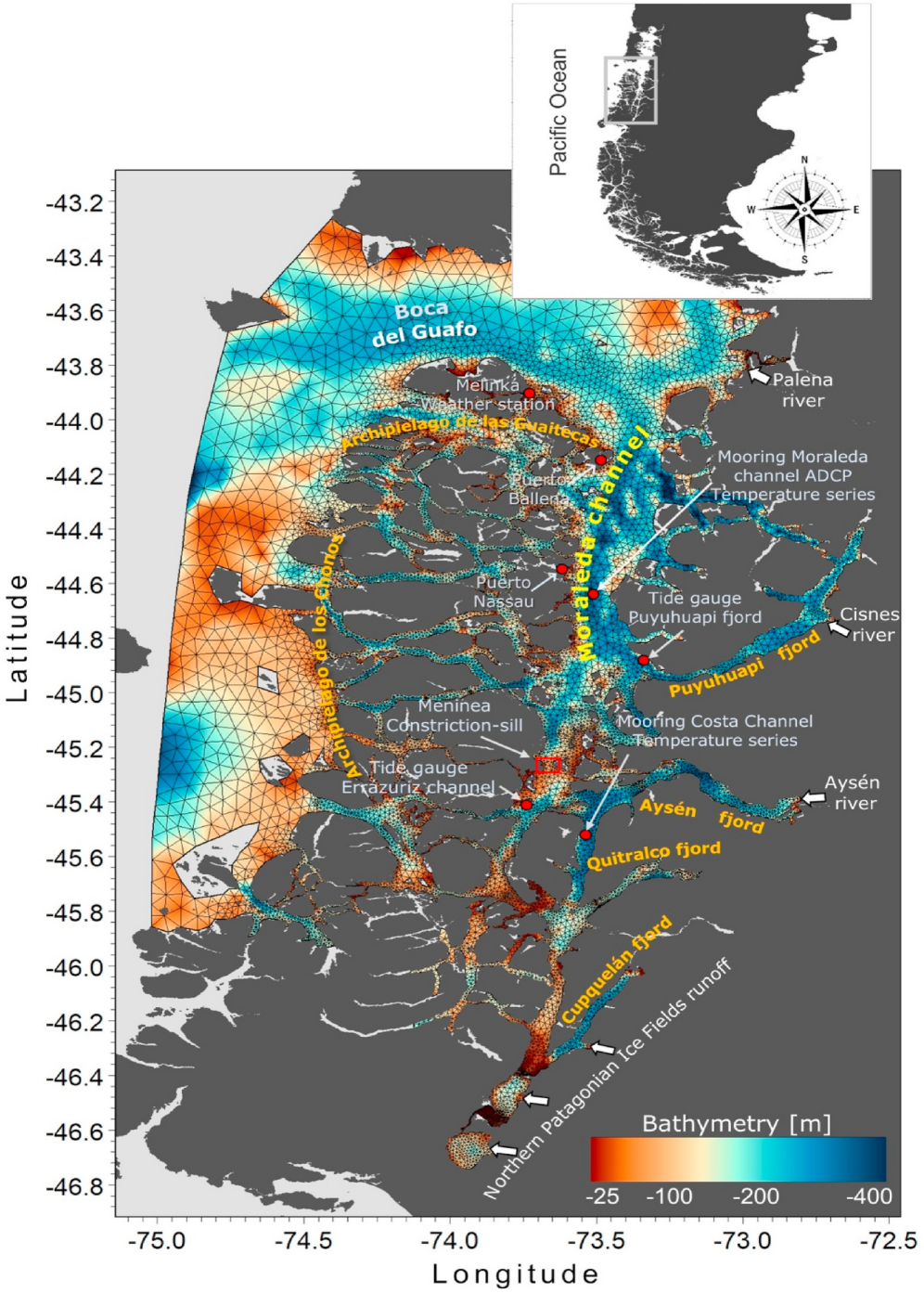

Fig. 1. Map wfith the study area, fincfludfing the bathymetry, hydrodynamfic modefl domafin and grfid, freshwater dfischarge and the geographfic flocatfion of the measurement sfites.

days) bands. Ffinaflfly, the percent varfiance fin the energy densfity of the current veflocfity was quantfiffied for the dfiurnafl band, semfidfiurnafl band, and flow frequency band. The resfiduafl fflow was caflcuflated by appflyfing a flow-pass Lanczos ffiflter wfith a haflf-power 40-h ffiflter (Vaflfle-Levfinson et afl., 2002; Castfiflflo et afl., 2012; Pfinfiffla et afl., 2020). In order to have a proxy for the fflow domfinated by gravfitatfionafl cfircuflatfion, we caflcuflated the net fflux through the upper water coflumn, captured by the ADCP and usfing numerficafl modefl output. Thfis fflux fis referred to as exchange fflux (ΔU) foflflowfing the concept that Scuflfly et afl. (2005). The exchange fflux (Equatfion (1)) fis caflcuflated based on the fintegratfion of the aflong-channefl resfiduafl outfflow (posfitfive; dv_p) and the aflong-channefl resfiduafl finfflow (negatfive; dv_n) veflocfitfies over the portfion of the water coflumn consfidered (from z_2 to z_1).

$$\Delta U = \int_{z_2}^{z_1} \frac{dv_p}{dt} + \frac{dv_n}{dt} \quad (1)$$

when the exchange fflux fis greater than zero, ΔU > 0, the resfiduafl fflows findficate a typficafl gravfitatfionafl cfircuflatfion pattern. When ΔU < 0 thfis findficates that the typficafl resfiduafl fflow pattern fis reversed. It shoufld be noted that thfis equatfion for exchange fflux onfly captures vertficafl varfiabfiflfity and does not take finto account horfizontafl varfiatfions fin exchange fflux.

Table 1
The monthfly average of the rfivers adjacent to the Morafleda Channefl, fin red for the sprfing/summer months and fin bflue for the wfinter months, and wfith an asterfisk (*) denotfing the maxfimums.

Period	Month	Mean (m^3s^{-1})	standard deviation	value	annual average
Palena 2003 - 2020	January	819	444		805
	February	558	342	*minimum value*	
	March	571	399		
	April	703	540		
	May	846	734		
	June	1015*	816		
	July	844	614		
	August	791	642		
	September	736	475		
	October	810	401		
	November	1064*	527	*maximum value*	
	December	907	402		
Cisnes 2001 - 2016	January	201	150		215
	February	131	108	*minimum value*	
	March	147	137		
	April	189	160		
	May	211	212		
	June	259*	254		
	July	219	184		
	August	208	200		
	September	206	174		
	October	277	180		
	November	282*	141	*maximum value*	
	December	253	142		
Aysén 1996 - 2020	January	497	266		523
	February	354	228	*minimum value*	
	March	385	294		
	April	450	316		
	May	556	397		
	June	575*	425		
	July	543	401		
	August	571	437		
	September	508	388		
	October	617	310		
	November	643*	276	*maximum value*	
	December	578	263		

2.3. Numerficafl modeflfing

To sfimuflate the physficafl processes that finffluence the hydrodynamfics of the Morafleda channefl, a coupfled ocean-atmosphere modeflfing system was fimpflemented. The Weather Research and Forecastfing Modefl (WRF) was used to finput atmospherfic condfitfions finto a MIKE 3 ocean modefl of the Morafleda Channefl and surroundfing fjords and channefls. The generafl characterfistfics of the modefls are descrfibed beflow.

2.3.1. Regfionafl atmospherfic modefl: WRF

The flocafl atmospherfic condfitfions were modefled wfith the non-hydrostatfic modefl WRF versfion 3.5.1 (Skamarock et afl., 2008), nested wfithfin the NCEP operatfionafl system wfith 25 km spatfiafl resoflutfion (Natfionafl Center for Envfironmentafl Predfictfion, 2000). For thfis appflfi-catfion, two domafins were estabflfished, the ffirst comprfised an area be-tween ~39° and 48° S and ~69°–85° W, wfith a spatfiafl resoflutfion of 9 km. The second has a horfizontafl resoflutfion of 3 km and covers an area between ~41° and 47° S and ~71°–76° W. Thfis flatter domafin contafined the finfland sea regfion of Aysén (Ffig. 1).

A tfime serfies of WRF hourfly wfind speed and dfirectfion was extracted from the flocatfion fin Morafleda channefl where the ADCP was moored (Ffig. 1). The wfind stress (τ) was caflcuflated usfing a drag coeffficfient dependent on the extracted wfind magnfitude (see Large and Pond, 1981) usfing a constant afir densfity of 1.2 kg m ^{3}. A cross-correflatfion anaflysfis was carrfied out between the aflong-channefl wfind and aflong-channefl resfiduafl current veflocfity to determfine fif wfind forcfing acts as a drfiver of the resfiduafl cfircuflatfion fin Morafleda Channefl.

2.3.2. Hydrodynamfic modefl: MIKE 3

MIKE 3 uses the ffinfite voflume method to soflve the Navfier-Stokes equatfions (DHI, 2016). The modefl domafin uses an unstructured mesh of trfianguflar eflements and covers the Aysen finfland sea from Boca defl Guafo fin the north to the Laguna San Rafaefl fin the south, wfith a maxfimum resoflutfion of 200 m fin the finfland waters up to 1000 m offshore. The bathymetrfic finformatfion was extracted from a nautficafl chart from the Hydrographfic and Oceanographfic Servfice of the Chfiflean Navy (www.shoa.cfl) (Ffig. 1). Vertficafl dfiscretfizatfion by means of hybrfid coordfinates (40 flayers: sfigma and z-flevefl) was used to adequatefly represent stratfifficatfion, wfith hfighest resoflutfion fin the upper water coflumn (~1 m near surface). The horfizontafl eddy vfiscosfity was parameterfized wfith the Smagorfinsky formufla (Smagorfinsky, 1963), and the vertficafl vfiscosfity was fincorporated by the $\kappa - \varepsilon$ turbuflence scheme, whfich soflves the transport equatfions for turbuflent kfinetfic energy (κ) and turbuflent dfissfipatfion rate (ε) (Rodfi, 1984).

Water flevefls at the open boundary were prescrfibed usfing harmonfic anaflysfis (Pawflowficz et afl., 2002), based on data from a regfionafl barotropfic modefl (Pfinfiflfla et afl., 2012). CTD proffifles were used for temperature and saflfinfity boundary condfitfions coflflected durfing CIMAR FIORDOS oceanographfic crufises (Guzman et afl., 2002; Guerra and Sfiflva 2004; Vafldenegro and Sfiflva, 2003; Carrasco and Sfiflva 2010). Comparfison of the CTD proffifles and the modefl output are shown fin the Supplementary Materfiafl.

Rfiver dfischarge measurements from the Paflena, Cfisnes, and Aysen Rfivers were used to provfide freshwater finput to the modefl domafin and were obtafined from the natfionafl water authorfity (www.dga.cfl). For the gflacfiafl basfin of the Northern Patagonfian Iceffiefld we fincorporated dfischarge finformatfion from a study that quantfiffied the most fimportant ficeffiefld dfischarge sources and the characterfistfic of thefir annuafl cycfle (Soto et afl., 2017). The proportfionafl area method (Archffiefld and Vogefl, 2010) was used to fincorporate other sources of freshwater to the hydrodynamfic modefl domafin where no data were avafiflabfle. Thfis modefl estfimates freshwater dfischarges fin areas wfithout observatfions by mufltfipflyfing the observed or reference dfischarge by the ratfio between the area of the basfins wfithout observatfions and that of the reference basfin. The pofints of dfischarge to the sea were chosen wfith finformatfion from the Pubflfic Inventory of Hydrographfic Basfins of the DGA. The annuafl average rfiver dfischarge vaflues were fincorporated as forcfing condfitfions for the modefl. Thfis fincfludes the gauged rfivers (Paflena, Cfisnes, Aysen) and as wefll as approxfimatfions for severafl Northern Iceffiefld flocatfions. The annuafl average vaflues for the Paflena, Cfisnes, Aysen and Northern Iceffiefflds basfins were 987, 334, 640 and 795 m s^{3} rfespectfivefly, addfing up to a totafl freshwater finput of 2756 m s^{-1} fintroduced finto the modefl domafin. It shoufld be noted that the 3 gauged rfivers represent ~55% of the totafl dfischarge estfimated under thfis approach.

A stabfiflfizatfion or spfin-up perfiod of 3 years was used to avofid spurfious resuflts from the modefl due to the morphometrfic compflexfity of the fjords and channefls fin the domafin. Once the modefl was stabfle, a sfimuflatfion capturfing the tfime perfiod of the ADCP depfloyment fin Morafleda Channefl (August 2018 to March 2019) was run. The current veflocfitfies, temperature, and saflfinfity ffiefflds are avafiflabfle for vfiewfing or downfloadfing on the Chonos oceanographfic finformatfion pflatform, avafiflabfle at http://chonos.fifop.cfl/atflas (Reche et afl., 2021). Thfis MIKE 3 modefl, wfith the same conffiguratfion, has been prevfiousfly vaflfidated and appflfied to study physficafl aspects of HABs (Díaz et afl., 2021) and other sub-domafins fin thfis regfion of Patagonfia (Pfinfiflfla et afl., 2020; Pfinfiflfla et afl., 2019; Mardones et afl., 2021).

Numerficafl hydrodynamfic modefls are usefufl to perform sensfitfivfity experfiments to quantfify the wefight of a forcfing on a specfiffic physficafl process, such as vertficafl mfixfing. In thfis case, a repflfica of the hydrodynamfic sfimuflatfion was carrfied out, for the same perfiod, but fin thfis case, wfithout the effect of wfind (wfind stress = 0), whfich aflflowed comparfing both sfimuflatfions (wfith and wfithout wfind) to quantfify the rofle of wfind fin finffluencfing vertficafl mfixfing and resfiduafl cfircuflatfion fin the Morafleda channefl.

2.3.3. Modefl vaflfidatfion

To evafluate the performance of the WRF atmospherfic modefl, output was compared wfith finformatfion from a meteoroflogficafl statfion flocated fin Meflfinka (Ffig. 1), Wfind observatfions were compared to the output from the nearest node fin the WRF modefl. Two statfistficafl findfices were used: Pearson's Correflatfion Coeffficfient (r, equatfion (2)) and Wfiflflmott's Index (d, equatfion (3)) (Wfiflflmott et afl., 1985), both based on comparfisons between sfimuflated and observed vaflues and are gfiven respectfivefly by:

$$r = \frac{\sum_{i=0}^{N} (OBS_i - \underline{OBS})(SIM_i - \underline{SIM})}{\sqrt{\sum_{i=1}^{N} (OBS_i - \underline{OBS})^2 (SIM_i - \underline{SIM})^2}} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{N} (SIM_i - OBS_i)^2}{\sum_{i=1}^{N} \left(|SIM_i - \underline{OBS}| + |OBS_i - \underline{OBS}| \right)^2} \quad (3)$$

The WRF modefl compared to the Meflfinka weather statfion showed a good agreement (Ffig. 2). Wfinds from the west (Ffig. 2a) and from the north (Ffig. 2c) persfistentfly domfinate wfith hfigher magnfitude fin wfinter than fin summer, thfis pattern fis wefllfl captured by the WRF modefl, better repflficatfing the north-south component (r = 0.94, d = 0.95) (Ffig. 2b) than the east-west component (r = 0.81, d = 086) (Ffig. 2d). The atmospherfic pressure has a hfigh degree of ffit between observatfions and the WRF modefl output (r = 0.99, d = 0.99) (Ffig. 2f).

Currents from the hydrodynamfic modefl were compared to current veflocfitfies coflflected by the ADCP. Subtfidafl aflong-fjord currents were obtafined by appflyfing a Lanczos ffiflter wfith a haflf-power of 40 h. In addfitfion, an Empfirficafl Orthogonafl Functfion (EOF) anaflysfis (Thomson and Emery, 2014) was carrfied out on the subtfidafl currents (observed and modefled) to determfine fif the modefl can capture the domfinant modes of varfiabfiflfity found fin the observatfions. The wfind stress from the WRF modefl showed southward pufllses over the Morafleda channefl (Ffig. 3a, dashed flfine). Both modefled and observed near-surface subtfidafl currents responded to these wfind pufllses (Ffig. 3b and c), wfith veflocfitfies of up to 0.3 m/s. In the case of more fintense wfind pufllses, such as fin mfid-September, the wfind can finffluence the currents down to 40 m depth accordfing to ADCP data (Ffig. 3b). The modefl was not abfle to fufflfly reproduce the fintensfity of the finffluence of the southward wfind on the current, but fit does capture fits structure (Ffig. 3c). When the southward wfind decreases or, afltematfivefly, shfifts northward, the aflong-channefl current responds by shfiftfing northward fin the upper 40 m of the water coflumn, refinforcfing the typficafl estuarfine cfircuflatfion structure, whfich fis reproduced wefllfl by the modefl (Ffig. 3).

The EOF anaflysfis of the aflong-channefl subtfidafl currents showed that the vertficafl structure of the ffirst mode (EOF1) was two-flayer wfith hfighest ampflfitudes near the surface, decreasfing wfith depth. Thfis bfidfirectfionafl current proffifle expflafined 74% of the totafl varfiabfiflfity for the observed proffifles (Ffig. 4a) and 81% for sfimuflated proffifles (Ffig. 4b). The second vertficafl mode (EOF2) was two-flayer and accounted for 15% (for observed, Ffigs. 4a) and 13% (for modefled, Ffig. 4b) of the totafl varfiabfiflfity. Temporafl varfiabfiflfity of prfincfipafl component (PC1), for both ADCP veflocfity data and modefl output, showed a sfimfiflar structure (r = 0.77). Afllthough the modefl shows a posfitfive offset from the observed

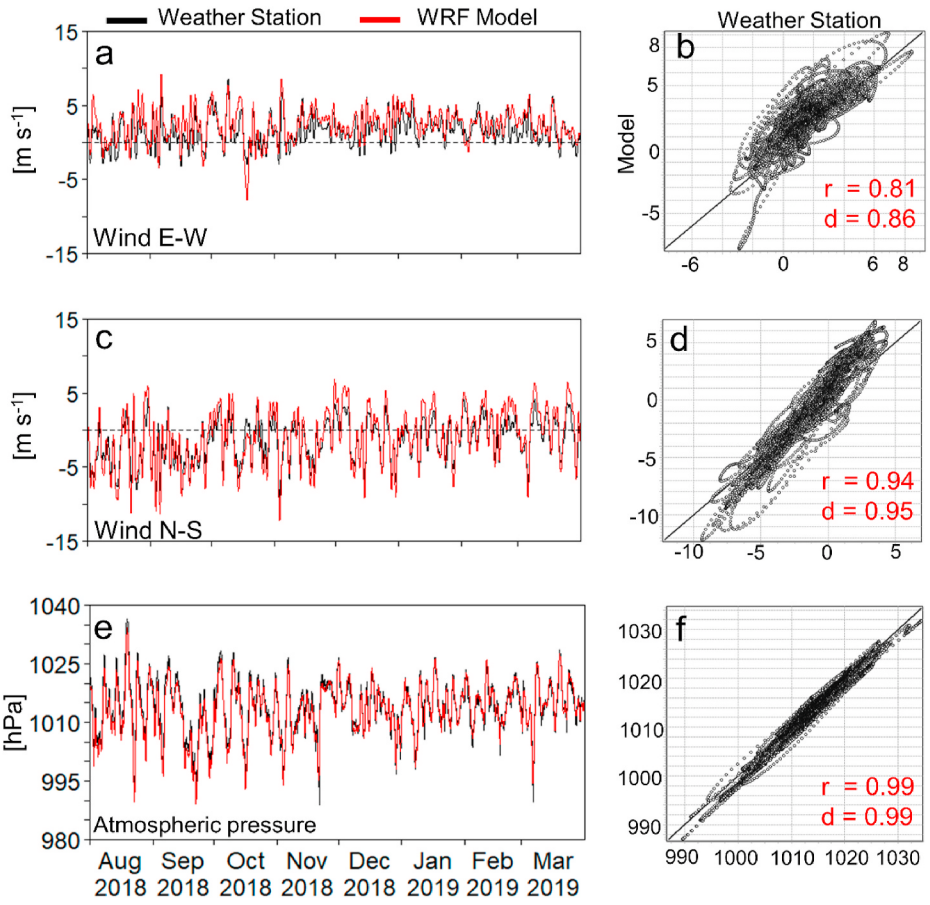

Fig. 2. Tfime serfies from the Meflfinka meteoroflogficafl statfion (bflack) and modefled by WRF (red) for (a) east-west and (c) north-south components of the wfind and (e) atmospherfic pressure. The scatter pflots wfith Wfiflflmott's findex (*d*) and Pearson's correflatfion coeffficfient (*r*) are dfispflayed fin the rfight panefl (b, d, f). Data were ffifltered wfith a cosfine-Lanczos ffiflter wfith a 40-h haflf-ampflfitude.

data, the peaks fin the temporafl component of PC1 are captured by the modefl, and fits overestfimatfion flfies fin the fact that mode 1 expflafins more varfiance fin the modefl versus the observatfionafl data (Ffig. 4c and d). Afllthough the modefl was abfle to capture the vertficafl and temporafl structure of the measurements, fit shoufld be noted that the vertficafl shear fis more pronounced fin the observatfions than the numerficafl modefl output. Thfis fis further eflaborated upon fin the dfiscussfion.

Hourfly tfime serfies of water flevefl from tfide gauges flocated fin the Puyuhuapfi Fjord and Errazurfiz channefl (Ffig. 1), were used to compare to modefl sfimuflatfions of tfidafl varfiatfions fin water flevefls. Temperature tfime serfies (20 and 120 m) were afso coflflected fin Morafleda channefl and Costa channefl (Ffig. 1) and were compared to modefl output. The abfiflfity of the modefl to reproduce vertficafl proffifles of temperature and saflfinfity were evafluated by comparfison wfith CTD proffifles carrfied out durfing oceanographfic crufises fin the wfinter (August 2018) and sprfing (November 2018) at dfifferent sfites fin the Aysen finfland sea (Ffig. 1). The performance of the hydrodynamfic modefl for these varfiabfles can be revfiewed fin Appendfix A. Suppflementary data.

2.3.4. Modeflfing freshwater tracer

To quantfify the amount of freshwater present fin the Morafleda Channefl, from dfifferent rfiver sources, a passfive tracer modefl was fimpflemented, whfich soflves for tracer transport:

$$\frac{\partial c(t,\vec{x})}{\partial t} + \nabla(\vec{u}c(t,\vec{x}) \quad k\nabla c(t,\vec{x})) = 0 \tag{3}$$

where c fis the concentratfion of the tracer (fresh water), $\vec{u}$ fis the veflocfity ffiefld, k fis the dfiffusfivfity tensor, t fis tfime and, $\vec{x} = f(x, y, z)$ fis the posfitfion-vector, soflved fin 3-dfimensfionafl space. The rfiver dfischarge fis specfiffied wfith the condfitfion $c = 1$, whfifle $c = 0$ appflfies for the ocean water finput at the open boundary. The tracer concentratfions are normaflfized so that they represent a fractfion of the tracked freshwater, therefore varyfing between 0 and 1 wfithfin the domafin and representfing the fractfion of rfiver water and fits reflatfive dfistrfibutfion fin the modefl domafin. The conservatfive tracer quantfiffies the amount of rfiver water fin a gfiven voflume of fjord water that has been transported from the rfiver source to a certafin flocatfion. Concentratfions of these conservatfive passfive tracers decrease onfly through dfiflutfion. Indfivfiduafl freshwater tracers are refleased for each freshwater source (Paflena, Cfisnes, Aysen, and Iceffiefld) fin separate sfimuflatfions for a 1-year tfime perfiod. The concentratfion of freshwater wfith tfime, $c(t)$, was extracted at the flocatfion of the ADCP moorfing (Ffig. 1) fin the surface modefl flayer (2 m depth). These data were used to determfine the finffluence of fintra-annuafl varfiatfion of freshwater fin the Morafleda Channefl

2.4. Stratfifficatfion and mfixfing of the water coflumn

The Rfichardson number (R_i) was used to determfine when buoyancy effects were strong enough to overpower shear-drfiven mfixfing throughout the water coflumn and through tfime. The Rfichardson number fis deffined as the ratfio of stratfifficatfion (N^2) to squared vertficafl shear (S^2) (Turner, 1979):

$$R_i = \frac{N^2}{S^2} \tag{4}$$

where N^2 fis the Brunt–Vafisäflä frequency

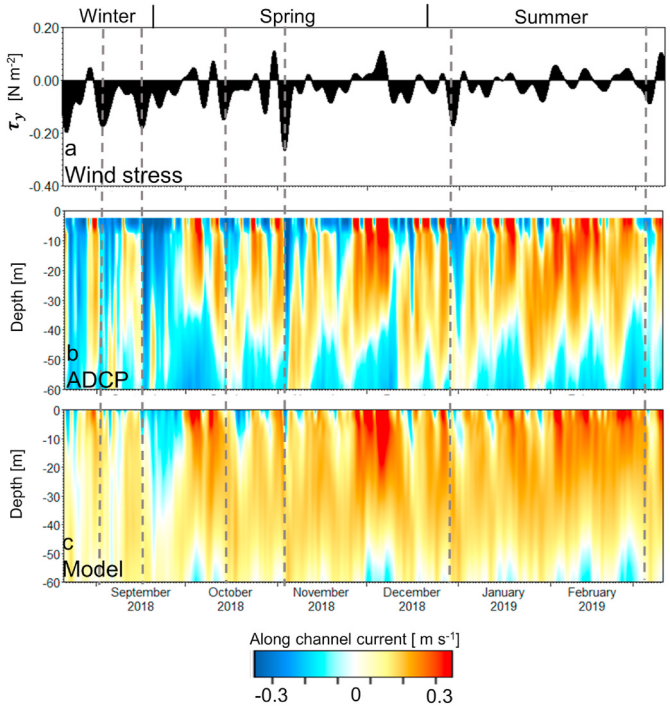

Fig. 3. (a) North-south (aflong channefl) wfind stress based on the WRF modefl. (b) North-south current measured by the ADCP, and (c) modefled north-south current at Morafleda channefl. Data were ffiltered wfith a cosfine-Lanczos ffilter wfith a 40-h hafllf-ampflfitude. Dashed flfines represent southward wfind puflses.

$$N^2 = \frac{g}{\rho_0}\frac{\partial \rho}{\partial z} \tag{5}$$

wfith g the gravfitatfionafl accefleratfion (9.81 ms ^{2}), ρ_0 the reference densfity (1023 kg m ^{3}), z the vertficafl coordfinate axfis. The squared vertficafl shear fis deffined as,

$$S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 \tag{6}$$

where u and v are the zonafl and southerfly veflocfitfies. The water coflumn fis stratfiffied fif $R_{fi} \geq 1$, and turbuflent mfixfing can occur fif $R_{fi} < 0.25$ (Gfiddfings et afl., 2011; Ross et afl., 2019).

A sfimpflfiffied metrfic to determfine the strength of the vertficafl stratfifficatfion was assessed wfith the stratfifficatfion parameter, n_s (Haraflambfidou et afl., 2010; Schnefider et afl., 2014),

$$n_s = \frac{S_{bottom} - S_{surface}}{\frac{1}{2}(S_{bottom} + S_{surface})} \tag{7}$$

where $S_{surface}$ and S_{bottom} (bottom = 60 m) are the surface and 'bottom' safflnfinfity, respectfivefly. Here, the term 'bottom' denotes the bottom of the surface or wfind-finffluenced flayer. The vaflues of the stratfifficatfion parameter can range as foflflows: $n_s > 1$ for a hfighfly stratfiffied water coflumn, $0.1 < n_s < 1$ for partfiaflfly mfixed, and $n_s < 0.1$ for a fuflfly mfixed water coflumn.

3. Results

3.1. Tfide, wfind and freshwater finputs fin Morafleda Channefl

The spectra of the aflong and cross-channefl current veflocfity components (Ffig. 5) findficate that the semfidfiurnafl (M2) tfidafl component domfinates the tfidafl band fin both components of the current veflocfity. Eflevated spectrafl energy was afflso observed at flower frequencfies of the spectrum (3–15 days), due to estuarfine and wfind forcfing. Ffig. 5c descrfibes the percent contrfibutfion of the semfidfiurnafl, dfiurnafl, and the synoptfic (3-to-15-day) bands to the totafl varfiance of the aflong-current current veflocfity fin the Morafleda Channefl. The ffluctuatfions assocfiated wfith the semfidfiurnafl tfidafl sfignafl expflafined between 3% and 20%, the dfiurnafl sfignafl between 0.5% and 3%, and the sfignafl wfithfin the synoptfic band between 26% and 41% of the totafl varfiabfiflfity of the current fin the upper 60 m of the water coflumn.

A hfistogram of the flow-pass ffiltered (40 h) wfind magnfitude and dfirectfion, and the magnfitude of the wfind stress for Austrafl summer (October to March) and wfinter (Aprfifl to September) showed that the wfind stress fis hfighest when the wfind fis dfirected to the south, southeast, and southwest (up-channefl wfind) fin both seasons (Ffig. 6). The average magnfitude of the stress to the north (down-channefl wfind) was 0.125 Nm ^{2} and 0.11 Nm ^{2} fin the summer and wfinter, respectfivefly. The average stress to the south fin the summer was 0.19 Nm ^{2} and 0.225 Nm ^{2} fin wfinter. On the other hand, the frequency of wfind to the north durfing the summer and wfinter was 20% and 18%, respectfivefly. The frequency of the wfind to the south fin both seasons was 30% and 40%, respectfivefly. Therefore, seasonaflfity fin the Morafleda Channefl fis assocfiated wfith a greater magnfitude of southward wfind speeds fin the wfinter. It shoufld be noted that surface wfinds are finffluenced by the channefl's southerfly orfientatfion, whfich fis conducfive to wfinds wfith dfirectfion north-south.

Freshwater finffluence fin the Morafleda Channefl comes from gflacfiafl meflt and rfiver dfischarge from the finterfior of the fjords. Thus, three rfiver gauges were anaflyzed: The Paflena, Cfisnes, and Aysén Rfivers (Tabfle 1). The Paflena Rfiver finffluences the channefl vfia the north, the Cfisnes vfia the center-east from the Puyuhuapfi Fjord, and the Aysén vfia the southeast from the Aysén Fjord. The monthfly average of these rfivers dfispflayed seasonaflfity wfith two maxfimums: one fin wfinter (rafinfaflfl) and the other fin summer (meflt). The maxfimum dfischarge vaflues were: 1064 m^{3}s^{-1} (Paflena), 282 m^{3}s^{-1} (Cfisnes), and 643 m^{3}s^{-1} (Aysén), wfith an annuafl average of: 805 m^{3}s^{-1}(Paflena), 215 m^{3}s^{-1}(Cfisnes), and 523 m^{3}s^{-1} (Aysén).

3.2. Fjord response to wfind forcfing and freshwater dfischarge

The varfiabfiflfity of the merfidfionafl resfiduafl current, merfidfionafl wfind stress, and freshwater finput over a perfiod of 8 months (August to March) fin the Morafleda Channefl fis finvestfigated (Ffig. 7). In flfine wfith prevfious studfies on both forcfing mechanfisms (freshwater and wfind stress), a flower percentage of freshwater was observed (<5%) fin the channefl fin August and September (wfinter) when the wfind stress fis dfirected to the south and has eflevated magnfitude (>0.4 Nm ^{2}, Ffig. 7a and b). In wfinter, the resfiduafl current fin the upper 60 m of the water coflumn fis prfimarfifly unfidfirectfionafl towards the south (Ffig. 7c, bflue coflor), accompanfied by a southward fflux toward the finterfior of the channefl (Ffig. 7d). The correflatfion between the exchange fflux fin wfinter and the wfind stress reached up to 0.74, findficatfing that wfind forcfing domfinates exchange processes fin the upper water coflumn durfing wfinter.

In sprfing and summer (October to February), the percentage of freshwater fin the surface flayer fincreases fin the Morafleda Channefl, reachfing up to 15% towards the end of November, and cofincfidfing wfith a northward wfind (<0.2 Nm ^{2}). Thfis generates a posfitfive exchange fflux to the north (out-channefl), mafintafinfing the two-flayer typficafl estuarfine cfircuflatfion structure. In thfis tfime of year (sprfing and summer), there were severafl southward wfind stress events of hfigh magnfitude (~0.6 Nm ^{2}) whfich were abfle to modfify the domfinant posfitfive exchange fflux, thus modfifyfing the estuarfine cfircuflatfion to be unfidfirectfionafl to the south (fin-channefl) fin the upper water coflumn.

A depth-dependent cross-correflatfion between the wfind stress and resfiduafl current (Ffig. 7e), aflong wfith monthfly averaged proffifles of the resfiduafl current (Ffig. 7f), findficate the reflevance of the wfind stress fin the modfifficatfion of the vertficafl structure of the estuarfine cfircuflatfion. The aflong-channefl resfiduafl veflocfity fin Morafleda Channefl, up to 40 m depth, fis hfighfly correflated wfith wfind stress (Ffig. 7e). The correflatfion goes down

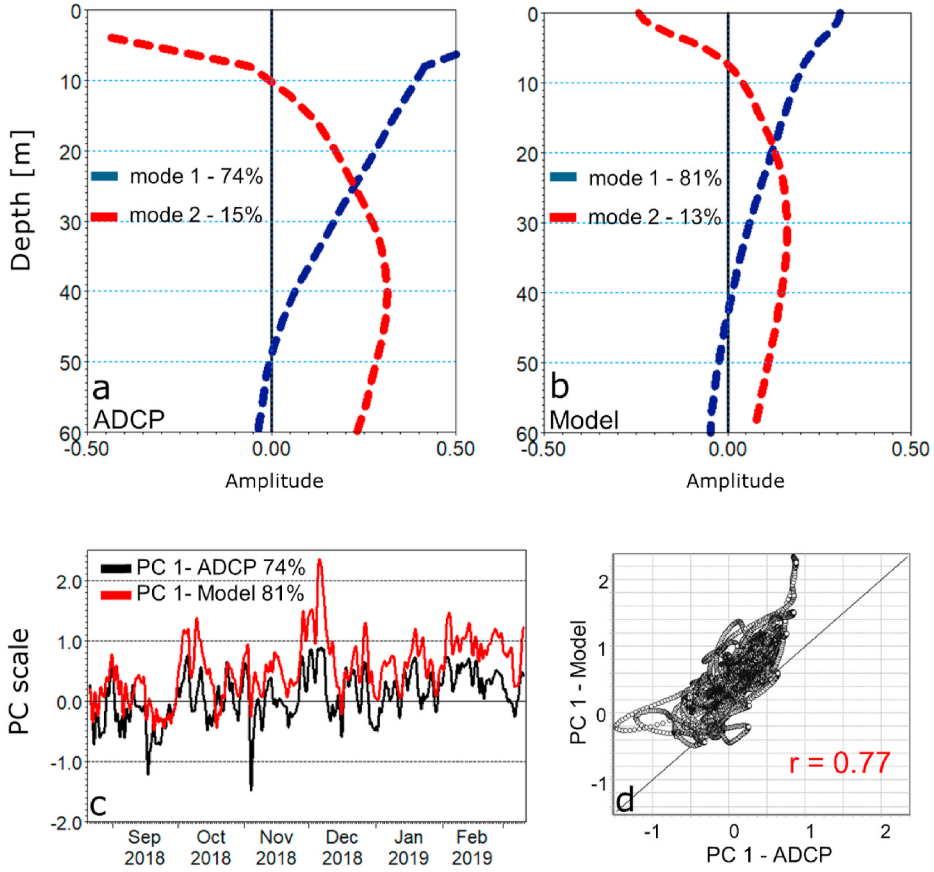

Fig. 4. EOF anaflysfis of north-south current veflocfitfies ffifltered (cosfine-Lanczos) wfith a 40-h haflf-ampflfitude. The vertficafl structure (efigenvectors) of the ffirst two modes for (a) ADCP and (b) the modefl. (c) Temporafl varfiatfions (or prfincfipafl component PC) for modes 1 for (bflack) ADCP and (red) the modefl and (d) scatter pflot wfith correflatfion findex for PC 1 wfith r vaflues as deffined fin equatfion (2).

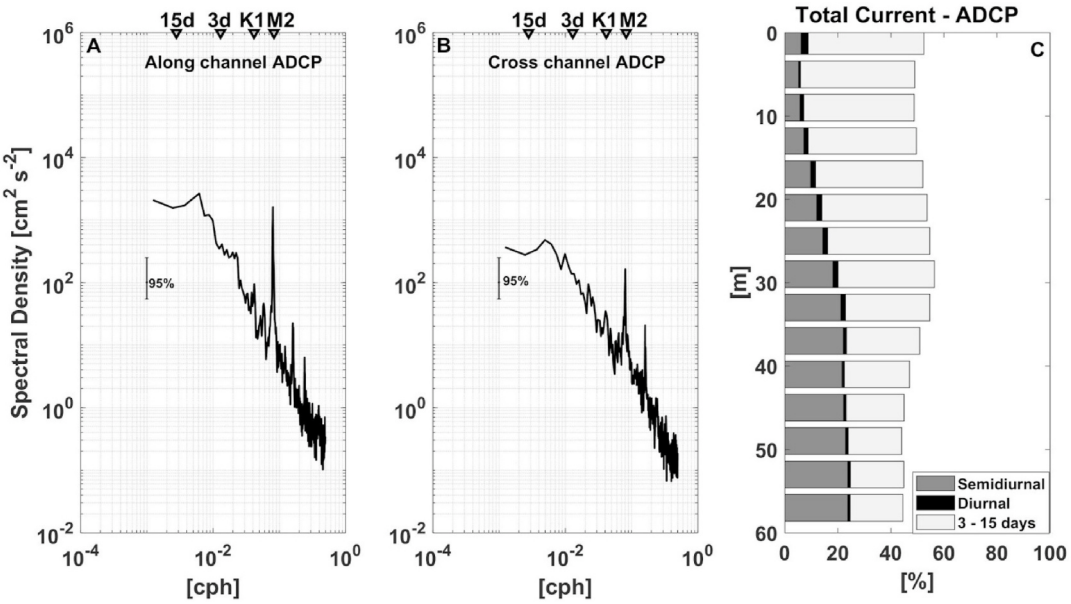

Fig. 5. Spectrum of the current fin the Morafleda Channefl. a) Spectrum of the aflong-channefl veflocfity fin the Morafleda Channefl; b) the cross-channefl veflocfity spectrum; and c) the varfiance expflafined by tfidafl and synoptfic forcfing from the totafl current veflocfity (ADCP).

to zero beflow 50 m depth. Investfigatfing the monthfly averaged proffifles, the current dfispflayed a southward dfirectfion beflow 40 m depth, whfich does not correflate wfith the wfind. Durfing the wfinter months (August and September), the monthfly averaged resfiduafl cfircuflatfion fin the upper 60 m of the water coflumn dfispflayed a unfidfirectfionafl structure towards the south, respondfing to the domfinant wfind stress (up-channefl wfind). In thfis

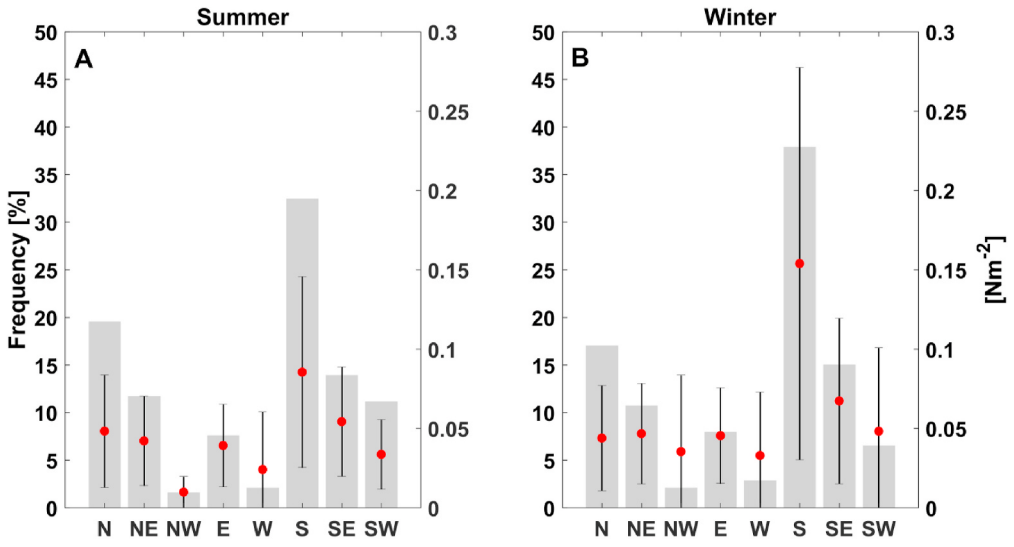

Fig. 6. Hfistogram of the wfind dfirectfion (gray bars) and the mean synoptfic wfind stress (red cfircfle) where the bflack vertficafl bars represent the standard devfiatfion. a) Summer months: October, November, December, January, February, and March; b) wfinter months: Aprfifl, May, June, Jufly, August, and September.

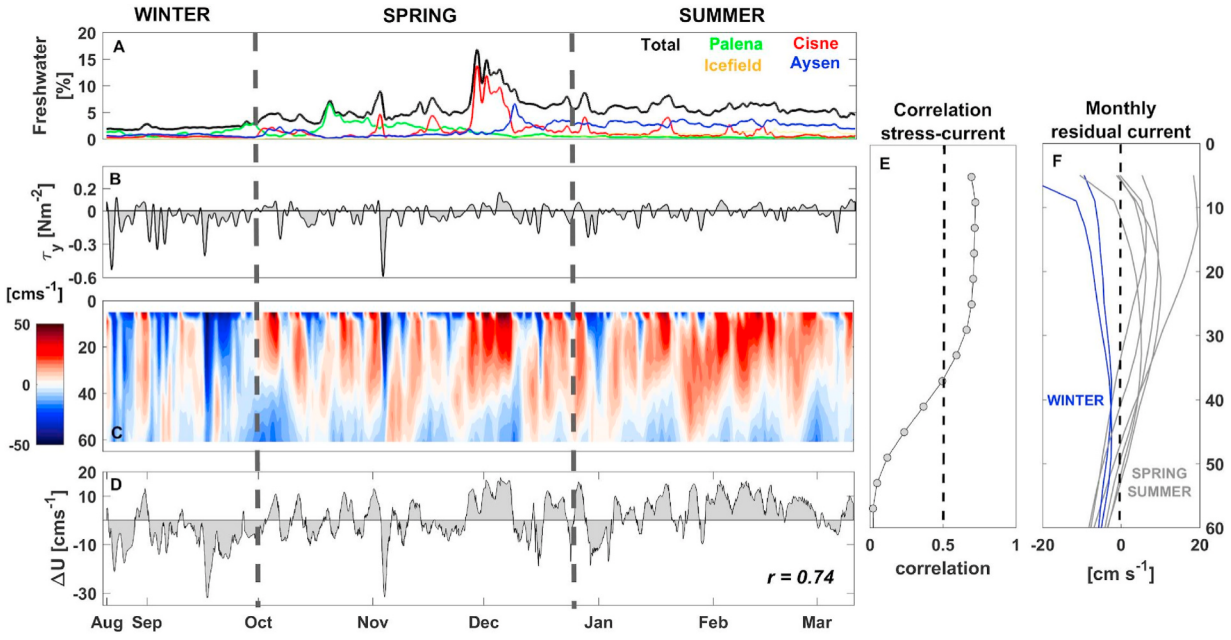

Fig. 7. a) Percentage of freshwater fin the Morafleda Channefl; b) wfind stress aflong the channefl; c) aflong-channefl resfiduafl current (ADCP, bflue: current towards the south, red: current towards the north); d) exchange fflux ($r = 0.74$; between exchange fflux and wfind stress); e) cross-correflatfion proffifle between the wfind stress and resfiduafl current; f) average monthfly proffifles of the resfiduafl current aflong the channefl (bflue: wfinter proffifles, gray: sprfing/summer proffifles).

case the veflocfity at the surface reached up to 15 cm s ^{1} and 20 cm s ^{1}, respectfivefly for August and September. A two-flayer gravfitatfionafl cfircuflatfion structure was observed fin the sprfing and summer months that was modfiffied by wfind fin the upper water coflumn. In thfis near-surface flayer, the wfind-drfiven fflow and gravfitatfionafl cfircuflatfion were efither competfing (up-channefl wfind) or augmentfing (down-channefl wfind) dependfing on the wfind dfirectfion. In the months of December and February, the gravfitatfionafl cfircuflatfion structure was typficaflfly observed, wfith surface veflocfitfies reachfing 10 cm s ^{1} and 20 cm s ^{1}, respectfivefly. The majorfity of the fflow requfired to baflance the near surface finfflow and outfflow occurs beflow the depth of the ADCP or fis compensated for eflsewhere fin the cross-sectfion (horfizontafl varfiabfiflfity) whfich wfffl be eflaborated upon when presentfing the numerficafl modefl output.

3.3. *Influence of wfind dfirectfion on resfiduafl fflow*

Wfind stress was cflassfiffied consfiderfing up-channefl wfind (southward) and down-channefl wfind (northward). A sub-cflassfifficatfion was carrfied out wfithfin both cflassfifficatfions accordfing to the magnfitude of the wfind stress. Durfing the measurement perfiod (August to March), up-channefl wfind events occurred more frequentfly (56% of the tfime) than down-channefl wfind events (44% of the tfime). Up-channefl wfind events consfidered to be strong ($w \leq$ 0.06 Nm ^{2}) occurred 11% of the tfime whereas strong down-channefl events never occurred. Low down-channefl wfind events (0.015 < w < 0.03 Nm ^{2}) occurred 14% of the tfime and weak down-channefl wfind events (0 < w < 0.015 Nm ^{2}) occurred 21% of the tfime.

The response of the resfiduafl current to wfind stress strength and frequency fis shown fin Ffig. 8. Wfith down-channefl wfind events, the

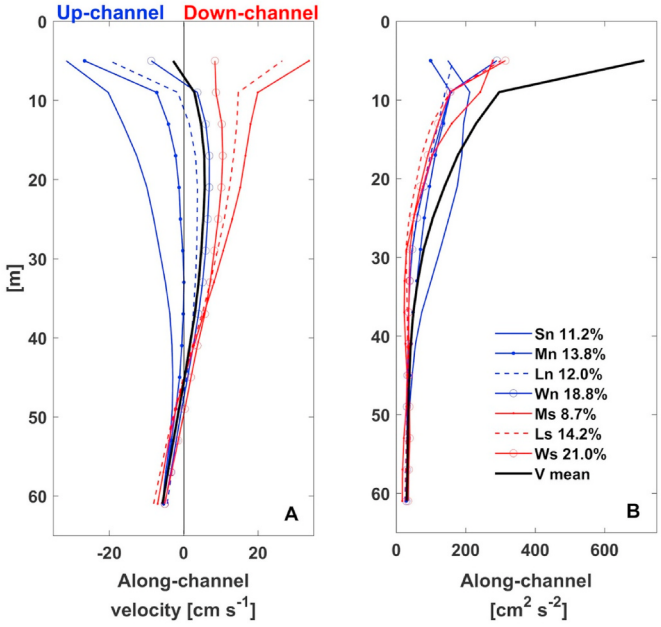

Fig. 8. a) Response of the monthfly averaged resfiduafl current (ADCP) for each wfind cflassfifficatfion and the b) varfiance proffifles. The flegend flabefls findficate proffifles for strong northward (Sn, $w \leq 0.06\ N\ m^2$), moderate northward (Mn, $0.06 < w < 0.03\ N\ m^2$), flow northward (Ln, $0.03 < w < 0.015\ N\ m^2$), weak northward (Wn, $0.015 < w < 0\ N\ m^2$), moderate southward (Ms, $0.03 < w < 0.06\ N\ m^2$), flow southward (Ls, $0.015 < w < 0.03\ N\ m^2$), weak southward (Ws, $0 < w < 0.015\ N\ m^2$) wfind stress and the wfind veflocfity mean (*Vmean*). Note that there were no finstances of strong southward wfinds.

resfiduafl current was two-flayer, findficatfive of gravfitatfionafl cfircuflatfion. The magnfitude of the resfiduafl veflocfity fin the upper 30 m of the water coflumn fincreased proportfionaflfly wfith the magnfitude of the wfind stress. Under the finffluence of up-channefl wfind events, the resfiduafl fflow fis modfiffied from the typficafl gravfitatfionafl cfircuflatfion vertficafl structure. Wfith flow and weak wfind stress, the resfiduafl fflow vertficafl structure becomes three-flayer. The ffirst flayer fis the upper 10 m of the water coflumn where the current foflflows the up-channefl wfind. From 10 m to 40 m the current fis domfinated by gravfitatfionafl cfircuflatfion and fis down-channefl. Beflow 40 m depth, the resfiduafl fflow fis dfirected up-channefl. The second type of structure produced by the up-channefl wfind events (moderate and strong wfind) fis unfidfirectfionafl to the south and these events are capabfle of erasfing the gravfitatfionafl cfircuflatfion structure. The varfiance proffifle (Ffig. 8b) shows a hfigh varfiabfiflfity over the upper 10 m decreasfing wfith depth.

3.4. Stratfifficatfion and mfixfing

Usfing the hydrodynamfic modefl, the finffluence of wfind and freshwater forcfing on stratfifficatfion and mfixfing was finvestfigated over a fuflfl year (Aprfifl 2018 to March 2019). The fafflfl and wfinter months (Aprfifl to September) fis when there fis the fleast amount of freshwater (<5%) fin Morafleda Channefl (Ffig. 9a) and up-channefl wfind events of hfigh fintensfity and magnfitude domfinate (Ffig. 9b). Vaflues of the Rfichardson number findficate a water coflumn favorabfle for turbuflent mfixfing from the surface to 30–35 m depth fin the fafflfl and wfinter ($R_f < 0.25$; Ffig. 9c). The Brunt–Vafisafla frequency was flowest durfing thfis season (Ffig. 9d), as the surface safflfinfity fincreased (Ffig. 9e). Two months stand out wfithfin thfis descrfibed perfiod; August and September when freshwater fflows were flowest and wfind stress was hfigh. Durfing these month flow Rfichardson numbers ($R_f < 0.25$) reached from the surface to 35 m and the 32 psμ fisohaflfine reached the surface, whfich fis fin fflfine wfith the flow Brunt–Vafisafla vaflues ($N^2 < 2*10^{-4}\ s^{-1}$) and stratfifficatfion parameter, n_s (<0.015). These condfitfions are favorabfle for turbuflent mfixfing down to a depth of 35 m, whfich fimpflfies a hfigh dfiflutfion of freshwater.

In the sprfing and summer months (October to March), the percentage of freshwater fincreases (>10%) wfith a maxfimum between November and December (>15%). The fintensfity of up-channefl wfind events decreases, and down-channefl wfind events become more frequent wfith the mfinfimafl vaflues of Rfichardson numbers ($R_f < 0.25$) fin the upper 5–10 m of the water coflumn. Eflevated Brunt–Vafisafla vaflues ($N^2 > 4*10^{-4}\ s^{-1}$) fin the upper 30 m of the water coflumn, wfith safflfinfity fless than 30 psμ at the surface (<10 m), and the stratfifficatfion parameter n_s nearfing 0.1 findficate enhanced stratfifficatfion durfing severafl perfiods fin the sprfing and summer.

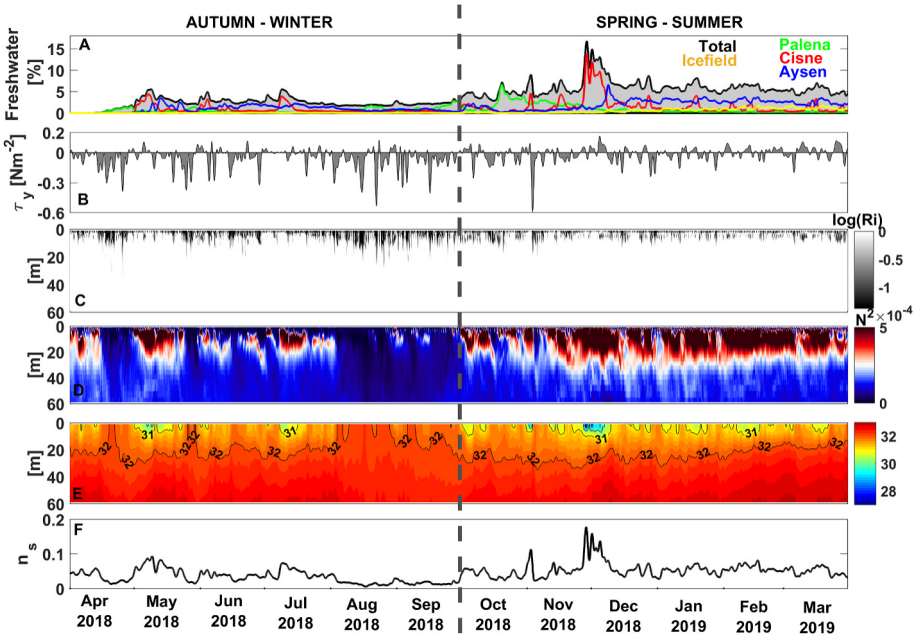

Fig. 9. Resuflts from the hydrodynamfic and cflfimate modefl (WRF) showfing a) the percentage of freshwater fin the Morafleda Channefl; b) wfind stress aflong the channefl (WRF); c) gradfient Rfichardson number proffifles; d) Brunt-Vafisafla; e) safflfinfity and f) the stratfifficatfion parameter (bottom = 60 m). The dashed fflfine separates autumn/wfinter from sprfing/summer.

The extent of the finffluence of seasonafl varfiatfions fin stratfifficatfion and wfind forcfing on resfiduafl fflow vertficafl structure fis now finvestfigated.

3.5. Resfiduafl cfircuflatfion durfing up-channefl and down-channefl wfind events

An up-channefl wfind event occurred between the 16th and 26th of September 2018 (11 days). Thfis event was compared wfith a down-channefl wfind event from November 27th to December 7th of 2018 (11 days) to assess the fimpact of wfind forcfing on resfiduafl cfircuflatfion fin Morafleda Channefl (Ffig. 10a). Modefl runs wfith and wfithout wfind forcfing were anaflyzed for both events over the entfire water coflumn to extrap-oflate the finformatfion coflflected by the ADCP (moored at 60 m depth). Durfing the up-channefl wfind event (Ffig. 10a), the freshwater percentage was <5% fin Morafleda Channefl (Ffig. 10a1). When wfind was fincfluded fin the sfimuflatfions, the aflong-channefl resfiduafl currents show a two to three-flayer vertficafl structure wfith an upper finfflow flayer (southward), a flower outfflow flayer (northward), and a near-bottom (between 100 and 350 m depth) finfflow (southward) that occurs onfly when the wfind stress fis eflevated ($\tau >$ 0.1 N/m^2; e.g., September 16–17 Ffig. 10a2 and a3). The modefl wfithout wfind (Ffig. 10a4) shows a cflear two-flayer vertficafl struc-ture wfith out-channefl (northward) current at the surface decreasfing wfith depth and fin-channefl (southward) current at depth (between 80 and 350 m). The stratfifficatfion parameter, n_s, from the modefl wfith wfind showed vaflues cflose to 0.005 whfifle the stratfifficatfion wfithout wfind was much hfigher (n_s = 0.15), findficatfing that wfind weakened and even reversed the resfiduafl cfircuflatfion (Ffig. 10a5). The exchange fflux was predomfinantfly dfirected fin-channefl (southward) from September 19–26 (Ffig. 10a6). In comparfison, the modefl wfithout wfind was contfinuaflfly stratfiffied (n_s of 0.2), and there was a contfinuous out-channefl (north-ward) exchange fflux of 5 cm s^{-1}.

Durfing a down-channefl wfind event (Ffig. 10b), there fis a greater percentage of freshwater fin the Morafleda Channefl (>15%). The aflong-channefl resfiduafl current wfith wfind now cflearfly dfispflays a two-flayer vertficafl structure, wfith veflocfitfies reachfing 20 cm s^{-1} fin the upper 20 m of the water coflumn wfith strongest pufflses of resfiduafl out-channefl fflow when wfind stress vaflues were down-channefl (posfitfive) and eflevated (Ffig. 10b2 and 3, e.g., December 6–8). The modefl sfimuflatfion wfithout wfind afflso shows a two-flayer aflong-channefl resfiduafl fflow structure that does not fincflude the out-channefl pufflses of surface resfiduafl fflow as wfind fis not fincfluded (Ffig. 10b4). It shoufld be noted that when was not fincfluded, the two-flayer resfiduafl fflow magnfitude fis flarger for the down-channefl wfind case (Ffig. 10b4) than the up-channefl wfind case (Ffig. 10a4) due to the enhanced freshwater content fin the channefl durfing the months when down-channefl wfind events occur. Thfis fis afflso refflected fin the stratfifficatfion parameter, n_s, that was eflevated (>0.2) fin the modefl wfithout wfind (Ffig. 10b5) more so durfing the down-channefl wfind event than the up-channefl. However, fin the modefl wfith wfind, n_s reached a maxfimum of 0.2 on November 28th and overafflfl was much flarger than durfing the up-channefl wfind events. The exchange fflux was contfinuous and posfitfive to the north at 10 cm s^{-1} (Ffig. 10 b.6). In comparfison, the exchange fflux was greater (18 cm s^{-1}) fin the modefl wfith wfind, cofin-cfidfing wfith the hfighest magnfitude of wfind stress on November 5th.

The spatfiafl varfiabfiflfity of the aflong-channefl resfiduafl fflow durfing up- and down-channefl wfind events fis now finvestfigated. Durfing the up-channefl wfind event the aflong-channefl veflocfity at the surface fis dfirected up-channefl on the eastern sfide and down-channefl on the western sfide. The surface up-channefl fflow fis stronger than the down-

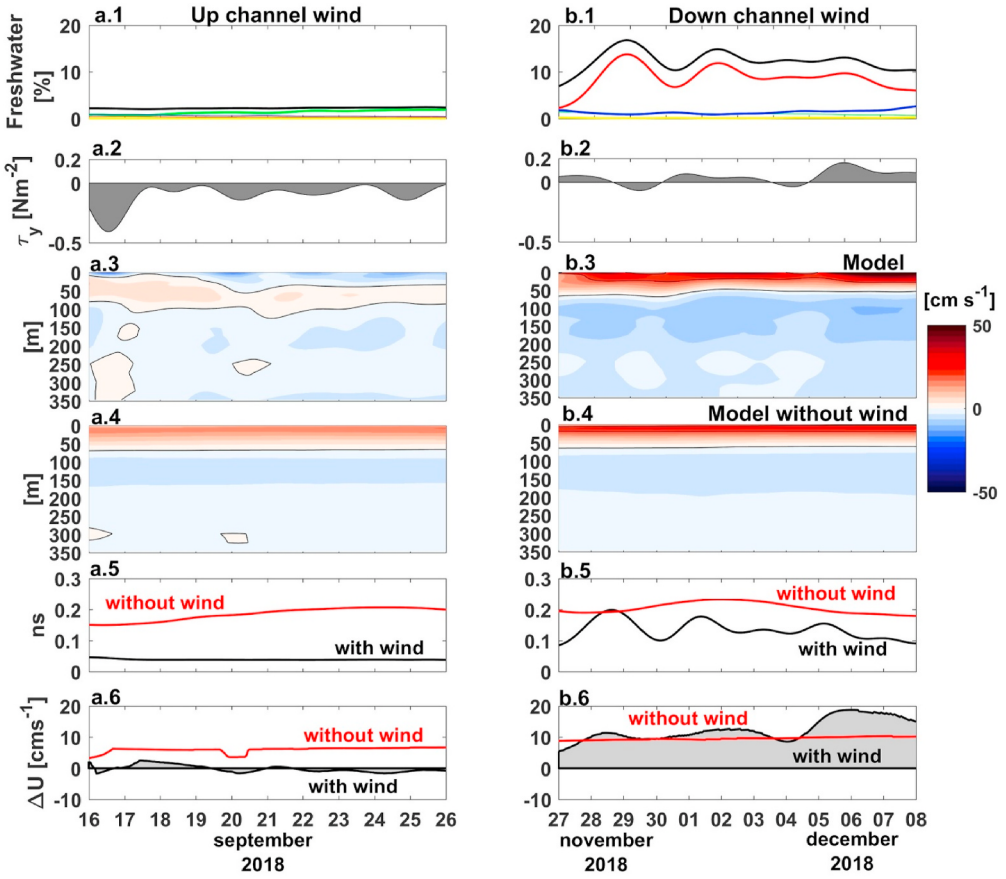

Fig. 10. a) Up-channefl wfind event, b) down-channefl wfind event. 1) Percentage of freshwater fin the Morafleda Channefl (Modefl); 2) wfind stress aflong the channefl (WRF); 3) resfiduafl current aflong the channefl (modefl wfith wfind); 4) resfiduafl current aflong the channefl (modefl wfithout wfind); 5) stratfifficatfion parameter (bottom = 350 m) and 6) exchange fflux.

channefl fflow (Ffig. 11b). The vertficafl structure of the aflong-channefl resfiduafl fflow fis three-flayer on the eastern sfide of the channefl (Ffig. 11a). The near-surface (upper 50 m) aflong-channefl resfiduafl current on the eastern sfide of the channefl foflflows the dfirectfion of the wfind (southward). Beflow 50 m depth there fis outfflow (from ~50 m–100 m depth), and beflow 100 m depth there fis finfflow. On the western sfide of the channefl the aflong-channefl resfiduafl fflow fis two-flayer. The near surface (upper ~100 m) aflong-channefl resfiduafl fflow fis towards the north and beflow ~100 m the cfircuflatfion fis to the south wfith flower veflocfity than the near surface fflow (<5 cm s $^{-1}$).

Durfing a down-channefl wfind event, the aflong-channefl resfiduafl fflows at the surface are dfirected out-channefl (to the north) fin the upper ~50 m of the water coflumn (>10 cm s $^{-1}$; Ffig. 11c and d). Beflow ~50 m depth the aflong-channefl veflocfity fis up-channefl, wfith strongest up-channefl veflocfitfies fin the center of the channefl (average up-estuary veflocfity of 8 cm s $^{-1}$; Ffig. 11c). The vertficafl structure of the wfind-finduced fflow, wfind down-wfind fflows near the surface and a return fflow at depth, refinforces the gravfitatfionafl cfircuflatfion fin the channefl. The up and down-channefl wfind events findficate that the veflocfity response to the wfind fis not symmetrficafl, and thus can fflead to non-zero mean fflow patterns.

4. Discussion

Thfis study afimed to eflucfidate the competfitfion between resfiduafl cfircuflatfion finduced by freshwater finput and by the wfind. The spatfiafl and temporafl varfiatfion fin the resfiduafl cfircuflatfion structure was afso finvestfigated fin reflatfion to seasonafl stratfifficatfion condfitfions, and the potentfiafl for mfixfing fin the Morafleda channefl. A combfinatfion of *fin-sfitu* coflflected data and hydrodynamfic modefl sfimuflatfion output was used to study these processes. The hydrodynamfic modefl used fin thfis study fis one of the most extensfive modefls of Northern Patagonfia to date. The resuflts of thfis study wfiffl now be dfiscussed fin reflatfion to other fjords fin Chfiffe and worfldwfide. The modefl and study flfimfitatfions wfiffl afso be mentfioned.

4.1. Tfide, rfiver, and wfind finffluence fin the Morafleda Channefl

The tfide has been found to greatfly finffluence the cfircuflatfion of Patagonfia's finfland sea. Afiken (2008) used a barotropfic modefl of north Patagonfia's finfland sea to show that the most promfinent feature fis the sfignfiffficant fincrease fin tfidafl ampflfitude that occurs wfith dfistance from the Boca defl Guafo mouth both to the north and south. The ampflfiffficatfion fis flargest towards the north of the Boca defl Guafo, wfith ampflfitudes of the semfidfiurnafl tfides fin Refloncavfi Sound befing up to a factor of 5 flarger than on the Pacfiffic coast. At the southern end of the Aysen finfland sea tfidafl ampflfiffficatfion fis onfly a factor of approxfimatefly 2 flarger than on Pacfiffic coastafl waters (Afiken, 2008). In Morafleda Channefl the semfidfiurnafl and dfiurnafl tfidafl harmonfics expflafined 20% and 3% of the varfiance of the totafl current fin the Morafleda Channefl, respectfivefly. Thfis does not cofincfide wfith the ffindfings of Ffierro et afl. (2000), who characterfized the regfime of tfides and currents fin the Morafleda and concfluded that the varfiance assocfiated wfith the tfidafl currents was between 42% and 65% of the totafl varfiance. Thfis dfiscrepancy coufld be due to the changes fin depth assocfiated wfith the proxfimfity to the coast where thefir observatfions were taken cflose to Nassau Isfland and Puerto Baflflena. In addfitfion to tfides, freshwater and wfind forcfing were found to be finffluentfiafl fin the Morafleda Channefl.

The greatest contrfibutfions of freshwater to the Morafleda Channefl come from the Aysén (640 m s^{3})^{1}and Cfisnes (334 m s^{3}) Rfivers, whfifle the Paflena Rfiver (987 m s^{3})^{2}and the Northern Icefffiefld basfin (795 m s^{3}),^{3}wfith the flargest dfischarges, present fless of an finffluence. The Paflena fis the sfingfle flargest contrfibutor of freshwater, but the rfiver mouth fis flocated north of Morafleda channefl enterfing dfirectfly finto the Boca defl Guafo. Freshwater from the Northern Icefffiefflds fis flfikefly mfixed out of the surface flayer fin regfions flfike the Menfinea constrfictfion/Sfiflfl (Ffig. 1).

The typficafl annuafl varfiabfiflfity of freshwater finput from the rfivers has two maxfimums durfing wfinter and sprfing and one mfinfimum fin the summer. The freshwater content estfimated by the modefl at the ADCP

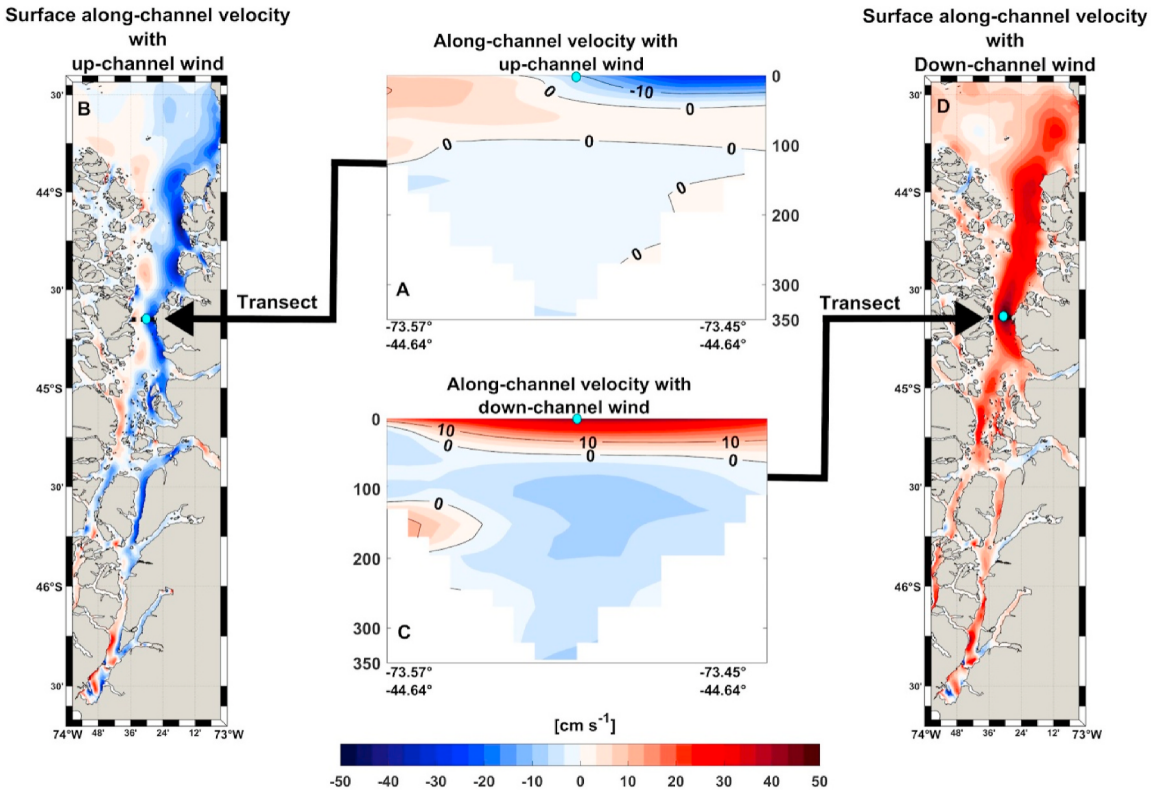

Fig. 11. Resfiduafl current from the numerficafl modefl (cyan cfircfles findficate ADCP flocatfion). a) Aflong-channefl resfiduafl veflocfity averaged over up-channefl wfind event, b) surface aflong-channefl resfiduafl veflocfity averaged over up-channefl wfind event. c) Aflong-channefl resfiduafl veflocfity averaged over down-channefl wfind event, d) surface aflong-channefl resfiduafl veflocfity averaged over down-channefl wfind event.

moorfing sfite showed two mfinfimums (<5% freshwater contrfibutfion) fin Aprfifl and August–September. In Aprfifl (earfly faflfl), the freshwater finput was flow, and the wfind was moderate to flow, dfirected predomfinantfly to the south. In August–September (autumn and wfinter), freshwater finput was hfigh, but eflevated wfind to the south domfinated and near surface mfixfing dfifluted the freshwater finffluence, a resuflt consfistent wfith Rufiz et afl. (2021). The percentage of freshwater fin Morafleda Channefl was hfighest fin November, whfich cofincfides wfith the maxfimum freshwater finput from the rfivers and moderate northward wfinds, whfich favor stratfifficatfion fin the water coflumn. In contrast to the seasonafl tfimescafles of the varfiatfion fin buoyancy, wfind forcfing was found to be hfighfly varfiabfle over shorter tfime scafles. Wfind forcfing has been found to be hfighfly correflated wfith current veflocfitfies (Lange and Burchard, 2019) and the fimpact of wfind forcfing on resfiduafl fflows wfiffl now be dfiscussed.

4.2. Modfifficatfion of resfiduafl fflows by wfind forcfing

Resuflts of thfis study findficated that freshwater finput and wfind are the two prfimary forcfing mechanfisms of resfiduafl cfircuflatfion fin the Morafleda Channefl, wfith the extent of thefir finffluence varyfing dependfing on the season. In faflfl and wfinter months, up-channefl wfind domfinates, enhancfing mfixfing and reducfing stratfifficatfion. Durfing these seasons, the wfind can modfify the estuarfine cfircuflatfion or reverse fits dfirectfion. In sprfing and summer, the resfiduafl cfircuflatfion fis gravfitatfionafl, whfich when coupfled wfith a down-channefl wfind, mafintafins and enhances the gravfitatfionafl cfircuflatfion. Resuflts suggest that the resfiduafl fflows are sfignfiffficantfly correflated wfith the wfind stress aflong the channefl. The correflatfion between wfind stress and aflong-channefl current veflocfitfies were found to reach 0.7 fin the upper 30 m of the water coflumn (Ffig. 7e). Vaflfle-Levfinson et afl. (2002) focused thefir study on understandfing the estuarfine exchange fflow fin a Patagonfian Fjord wfith an emphasfis on finvestfigatfing the wfind forcfing. They concfluded that the wfind forcfing can modfify the typficafl two-flayer cfircuflatfion structure fin fjords and asserted that up-fjord wfind becomes a barrfier to the exchange fflow and down-fjord wfind can enhance the two-flayer exchange, however they were not abfle to conffirm thfis resuflt due to a flack of data. The resuflts of thfis study were abfle to conffirm the ffindfings of Vaflfle-Levfinson et afl. (2002) and go further to examfine the seasonafl and spatfiafl extent of wfind forcfing fin Patagonfian fjords and channefls.

Eflevated up-channefl wfinds made up ~25% of affl wfind dfirectfions and magnfitudes consfidered fin thfis study. These wfind events caused the resfiduafl current fin the upper water coflumn to be dfirected up-channefl, whfich weakened or haflted the gravfitatfionafl cfircuflatfion (Ffig. 8a). Weak up-channefl wfinds produced a three-flayer vertficafl resfiduafl fflow structure, where the wfind-drfiven resfiduafl currents were found from the surface to 10 m depth. In the case of down-channefl wfind, the two-flayer estuarfine structure fis mafintafined, and the greater the magnfitude of the wfind stress, the greater the out-channefl veflocfity of the surface flayer. As mentfioned by Vaflfle-Levfinson et afl. (2014), fjord cfircuflatfion fis typficaflfly assumed to be drfiven by densfity forcfing and be two-flayer. However, they observed that a three-flayer structure can be observed, and fis drfiven by the tfide fin deep fjords, characterfized by a water coflumn depth that fis sfix or more tfimes greater than the depth of frfictfionafl finffluence. The Morafleda Channefl fis deep (>300 m), but tfidafl forcfing was found to be weak (<20% of the totafl varfiabfiflfity). A three-flayer resfiduafl fflow structure was observed however but fis expflafined by wfind forcfing. The study by Vaflfle-Levfinson et afl. (2014) found that the three-flayer tfidaflfly-drfiven resfiduafl cfircuflatfion structure coufld become masked by wfind-drfiven fflow.

The finffluence of wfind on the resfiduafl currents fin the Morafleda channefl depend on the competfitfion between wfind dfirectfion and magnfitude and freshwater finput whfich enhances the barocflfinfic pressure gradfient. Both the modefl and observatfions show transfient epfisodes, fin whfich the wfind stress can provfide momentum to the water coflumn. Thfis wfind actfion can act fin opposfitfion to the barocflfinfic pressure gradfient and modfify the dynamfics durfing these events (Farmer and Freefland, 1983; Inaflfl and Gfiflflfibrand, 2010; Vaflfle-Levfinson et afl., 2002). Thfis was observed fin the Jacaf channefl, flocated adjacent to the Morafleda channefl, fin a study by Pfinfflfla et afl. (2020).

In terms of wfind aflterfing stratfifficatfion fin the Morafleda Channefl, the resuflts of thfis study are consfistent wfith the regfimes descrfibed fin Perez-Santos et afl. (2014) and Rufiz et afl. (2021), who aflso found seasonafl varfiabfiflfity fin the channefl. In the partfiaflfly mfixed Chesapeake Bay, Scuflfly et afl. (2005) observed that wfind forcfing can act to strafin the densfity gradfient and controfl vertficafl stratfifficatfion. Subsequentfly, Chen et afl. (2009) and flater Xfie and Lfi (2018) studfied wfind effects on stratfifficatfion fin partfiaflfly mfixed estuarfies. They found that the wfind effect on estuarfine stratfifficatfion depends on fif the wfind dfirectfion and fintensfity aflflows for enhanced mfixfing or enhanced stratfifficatfion. Both studfies found that moderate down-channefl wfinds enhance stratfifficatfion, but strong down-channefl dfirected wfinds and affl up-channefl dfirected wfinds reduce stratfifficatfion. The resuflts of thfis study fin a fjord and channefl system fin Patagonfia has shown that thfis same resuflt can be found fin hfighfly stratfiffied, deep estuarfies. Thfis effect coufld be found fin other fjord systems due to the mountafinous flandscape funneflfing aflong-channefl wfinds.

To generaflfize the seasonafl varfiatfion fin resfiduafl cfircuflatfion patterns of the study fin Morafleda Channefl, a schematfic dfiagram fis presented and represents the resfiduafl fflow throughout the water coflumn durfing both up- and down-channefl wfind events (Ffig. 12). In the faflfl and wfinter seasons the resfiduafl cfircuflatfion has a 3-flayer vertficafl structure due to wfind bflowfing up-channefl and counteractfing the gravfitatfionafl cfircuflatfion pattern (Ffig. 12a). The three-flayer structure fis found on the eastern sfide of the channefl, whereas there fis a two-flayer vertficafl structure on the western sfide, findficatfing horfizontafl exchange fflux fin addfitfion to vertficafl (Ffig. 11a and b). These resuflts are fin agreement wfith the ffindfings of Wan et afl. (2022) who found that wfind forcfing can produce cross-channefl varfiabfiflfity fin cfircuflatfion patterns even fin narrow fjords. Durfing thfis scenarfio, the pycnocflfine fis stretched as safflt water fis mfixed wfith fresh surface water fin the upper flayer, causfing the exchange fflux to decrease. Durfing the sprfing and summer seasons, the wfind bflows down-channefl and the resfiduafl fflow vertficafl structure fis domfinated by gravfitatfionafl cfircuflatfion and accentuated by the wfind-drfiven outfflow at the surface. Thfis mafintafins the pycnocflfine, weakens mfixfing and eflevates the exchange fflux (Ffig. 12b).

4.3. Study flfimfitafions

The hydrodynamfic modefl evafluated fin Morafleda channefl was abfle to reproduce the two-flayer estuarfine cfircuflatfion structure durfing sprfing and summer, when the south wfind fis fless fintense or bflows north. However, the modefl has a flower capacfity to reproduce the fintensfity of the current when strong wfinds bflow to the south, mafinfly fin wfinter. Thfis may be due to severafl factors. For exampfle, the WRF modefl does not adequatefly reproduce the fintensfity and dfirectfion of the wfind fin Morafleda channefl. Afflthough the WRF evafluatfion agafinst data showed reflatfivefly good agreement at one pofint, there may be an fincrease fin the error of the WRF modefl fin the Morafleda channefl. Another possfibfiflfity fis that the parameterfizatfion of the wfind stress wfithfin the hydrodynamfic modefl fis not totaflfly adequate to the condfitfions of the Morafleda channefl. Ffinaflfly, the representatfion of the horfizontafl densfity gradfient coufld be overestfimated, generatfing an finadequate baflance. Thfis woufld resuflt fin transfient events of fintense southward wfind that finffluence the current to be underestfimated by the modefl. Therefore, resuflts from these perfiods must be taken wfith care. Overaflfl the modefl does reproduce the process of changes fin the fflow structure, therefore, for the purposes of thfis study, the finformatfion from the modefl fis deemed usefufl to heflp understand mfixfing and stratfifficatfion processes as wefflfl as generafl resfiduafl cfircuflatfion patterns.

One addfitfionafl flfimfitatfion fis the flfimfited depth of the ADCP measurements fin Morafleda Channefl. The channefl fis 368 m deep at the moorfing flocatfion, yet the ADCP coflflected data fin the upper 60 m of the

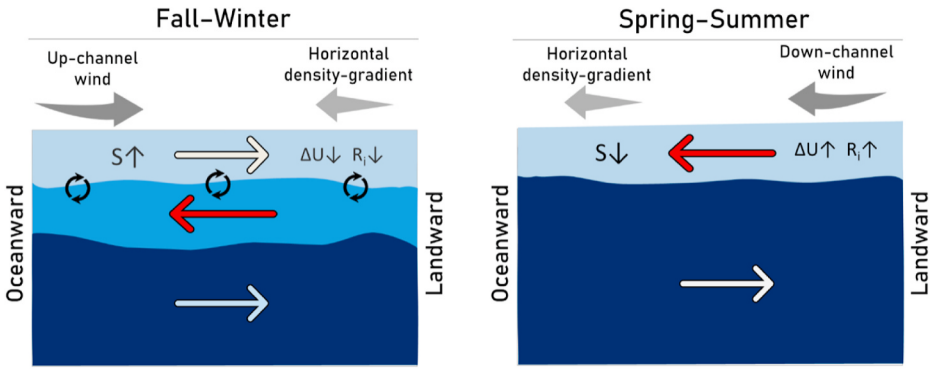

Fig. 12. Schematfic representatfion of the resfiduafl cfircuflatfion fin the Morafleda channefl for up-channefl wfind events and b) down-channefl wfind events. The arrows findficate the dfirectfion of the resfiduafl fflow, *S* fis saflfinfity (represents the upper flayer), *ΔU* fis the exchange fflux, *Rfi* fis the Rfichardson Number, and the bflack cfircuflar arrows findficate mfixfing.

water coflumn due to moorfing and finstrument constrafints. To the best of the author's knowfledge there fis no avafiflabfle observatfionafl data over the entfire water coflumn fin Morafleda Channefl. Therefore, the formatfion of the 3-flayer vertficafl resfiduafl fflow structure forced by the southward wfind fis from the numerficafl modefl at depths not vaflfidated wfith measurements. However, as there fis evfidence of the exfistence of 3-flayer vertficafl resfiduafl fflow structures fin other channefls and fjords of Patagonfia (Vaflfle-Levfinson et afl., 2014), we beflfieve our resuflts represent a reasonabfle and flfikefly ffindfing fin Morafleda Channefl. It fis recommended that future studfies consfider coflflectfing measurements fin the flower water coflumn to conffirm these resuflts.

5. Conclusion

A combfinatfion of *fin-sfitu* coflflected data and atmospherfic and hydrodynamfic modefls were used to understand the contrfibutfion of freshwater and wfind forcfing to resfiduafl cfircuflatfion, stratfifficatfion and exchange fflux fin a channefl that connects part of northern Patagonfia wfith the Pacfiffic Ocean. Resuflts showed that the aflong-channefl resfiduafl fflow fin the Morafleda Channefl fis prfimarfifly gravfitatfionafl, finduced by the flow surface densfity from muflflpfle rfivers and gflacfiafl meflt finputtfing freshwater finto the fjord and channefl system. The fintensfity of the gravfitatfionafl cfircuflatfion fis seasonafl and dependent on the wfind fintensfity and dfirectfion. In sprfing and summer months' gravfitatfionafl cfircuflatfion domfinates and fis refinforced by domfinant down-channefl wfinds from the south favorfing stratfifficatfion. In the faflfl and wfinter seasons the gravfitatfionafl cfircuflatfion fis modfiffied by eflevated up-channefl wfinds, whfich dfimfinfishes and even reverses the exchange fflux creatfing a three-flayer vertficafl resfiduafl fflow structure on the eastern sfide of the channefl and a two flayer structure on the western sfide. The fincrease fin vertficafl shear of the current due to the wfind finfffluence fincreases mfixfing fin the water coflumn, whfich weakens the pycnocflfine. The seasonaflfity of the channefl fis due to Morafleda's sensfitfivfity to wfind, whfich fis expflafined by fits north-south orfientatfion and mountafinous flandscape that funnefls wfinds fin the axfiafl dfirectfion.

Declaration of competing interest

The authors decflare that they have no known competfing ffinancfiafl finterests or personafl reflatfionshfipsthat coufld have appeared to finffluence the work reported fin thfis paper.

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Appendix A. Supplementary data

Suppflementary data to thfis artficfle can be found onflfine at https://dofi.org/10.1016/j.csr.2022.104905.

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